Physical Processes of the northern Gulf of Mexico and their influence on Hypoxia of the Texas-Louisiana Shelf

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Abstract

The continental shelf of the northern Gulf of Mexico is host to a myriad of physical processes that can influence the spatial and temporal structure of the hypoxic zone off coastal Louisiana. The timing, frequency of occurrence, and relative strength of these processes can combine to enhance or inhibit the mechanisms responsible for hypoxia. We discuss how the biological processes that cause hypoxia are controlled by the physical structures associated with the Mississippi and Atchafalaya freshwater plumes and how the structures change from east to west on the shelf. We summarize the known physical processes affecting the waters of the northern Gulf of Mexico and discuss how these processes contribute to the setup or breakdown of water column stratification and their affect on the delivery of nutrients to the continental shelf. Temporal scales of the physical processes range from seconds to seasonal and inter-annual periods, while horizontal spatial scales range from tens of meters to hundreds of kilometers. Extreme events like hurricanes and severe flooding or drought can also profoundly affect the spatial and temporal distribution of hypoxia. Also considered are the potential role of climate change in altering the physical processes of the shelf and the potential affect this may have on hypoxia. Lastly, we identify knowledge gaps in the understanding of the physical processes important to the distribution of hypoxia and make recommendations for action to fill those gaps.

1. Introduction

Each summer, the largest area of hypoxic bottom water in the western Atlantic coastal zone develops in the northern Gulf of Mexico on the continental shelf south of Louisiana (Rabalais et al., 2002a). The size of this zone has averaged over 15000 km^2 annually since 1993, its area in 2006 being 17200 km^2. Hypoxia is defined by dissolved oxygen concentrations below 1.4 ml/l, and is dependent on the combined effects of excessive nutrient loading (often leading to eutrophication; Rabalais et al., 2006b) and a stable water column resulting from thermal heating and capping by freshwater. Dissolved oxygen concentrations are affected by the relative balance between photosynthesis, respiration, diffusion, and advection. An increase in water column stability inhibits the downward diffusion of oxygen through the pycnocline (the layer where density change with depth is at a maximum; Wiseman et al., 1997; Rabalais et al., 1999). This leads to respiration below the pycnocline exceeding photosynthesis or other source processes, so that the oxygen concentration in the bottom layer becomes severely depleted (Figure 1).

It is generally believed that the combined effects of winds and gravity waves break down the stratification and are responsible for the re-oxygenation of the bottom water as oxygen rich surface water is mixed downward in the water column.

Historically, these relative effects of nutrient loading and water column stability have been difficult to separate because both are enhanced by increased freshwater flux to the shelf. In this paper, we describe the principal physical forcing mechanisms of the northern Gulf of Mexico and how these mechanisms can affect the areal extent, severity, and duration of hypoxic conditions on the eastern Texas-Louisiana Shelf. We begin with a description of the physical characteristics of the region and the general circulation patterns known to exist on the shelf. Section 2 focuses on the principal driving mechanisms and how they are related to controlling hypoxia and includes a discussion of potential effects of global scale climate change on the hypoxic zone. Section 3 speculates on the possible influence of global scale climate change on the physical processes of the Gulf of Mexico and how that may affect hypoxia on the shelf. Section 4 presents a discussion of knowledge gaps in the understanding of how physical processes affect hypoxia with recommendations for filling in those gaps. Finally, Section 5 summarizes the principal findings of how physical processes influence hypoxia on the Texas-Louisiana Shelf.

1.a. Physical description of the region

The Gulf of Mexico is a semi-closed basin with both broad and narrow continental shelves surrounding a deep abyss reaching ~3800 m and is connected to the world ocean through entrances at the Yucatan Channel and Florida Straits. The principal drivers of the large-scale physical processes of the Gulf of Mexico are wind, currents associated with the Loop Current System, and tides (see Sturges and Lugo-Fernandez (2005) and references therein). The circulation and physical processes that occur in the deep Gulf of Mexico along with the local processes of wind forcing, river discharge, and other processes (e.g., tides, topographical steering) occurring on the Texas-Louisiana Shelf combine to control the vertical and horizontal density structure as well as the distribution of freshwater and biogeochemically important properties on the shelf. Because density stratification controls the rate of vertical mixing of atmospheric oxygen across the pycnocline, the temporal and spatial variability of physical processes on the shelf can have a profound affect on the temporal and spatial variability of dissolved oxygen concentrations beneath the pycnocline on the Texas-Louisiana Shelf. As will be shown, the relative strength and timing of *physical* events and processes can have direct and indirect impacts on the timing and strength of the *biogeochemical* processes that occur on the shelf. Although there have been many studies of the region regarding circulation dynamics and physical processes, there is very little quantitative information regarding the relative roles of those processes in controlling the areal extent, severity, and duration of hypoxia.

On the Texas-Louisiana shelf, the physical drivers have widely varying temporal and spatial scales. The basic description of the general circulation of this shelf has been the subject of several investigations (Cochrane and Kelly, 1986; Cho et al., 1996; Nowlin et al., 1998; Nowlin et al., 2005). The central tenet of the Cochrane and Kelly (hereafter CK) hypothesis states that the circulation of the inner shelf is seasonally driven; downcoast (in the sense of the propagation direction of a shelf wave, i.e., from Louisiana toward Texas) components of wind drive downcoast currents in nonsummer months (Figure 2; approximately September through June). In May and June, the prevailing winds acquire an upcoast component (Figure 3), which appears first along the Mexican shelf and gradually moves north and on to the Texas coast. This upcoast wind drives a reversal of the coastal current towards the east. In July, the reversal generally reaches coastal Louisiana. In late August and September, downcoast winds are re-established and downcoast coastal currents again tend to dominate the circulation of the inner shelf. This basic pattern of seasonal alternating downcoast and upcoast coastal currents is thought to be robust but with interannual variability.

Researchers have also looked at the variability of physical and hydrographic properties on interannual time scales (Li et al, 1996), as well as processes at much shorter (i.e., inertial and tidal) time scales (Chen et al., 1996; DiMarco and Reid, 1998; DiMarco et al., 2000). Wang (1996) confirmed the annual cycle of winds and its effects on inner shelf currents proposed by CK using objectively analyzed winds and observed currents from April 1992 through November 1994. For the same period, Cho et al. (1998) constructed monthly streamfunction fields based on current meter data and examined the quasi-annual circulation pattern using empirical orthogonal functions (EOFs) of the streamfunction fields. That study confirmed the CK circulation scheme from direct current velocity observations and showed that the dominant mode contained 90% of the low-frequency (monthly and longer periods) variability and was highly correlated with the along-shelf wind stress.

The long-term mean flow of the Texas-Louisiana Shelf suggests the shelf is divided into two regimes at roughly the 50-m isobath (Nowlin et al. 2005). Inshore of 50-m the mean flow is downcoast; offshore of 50-m, it is upcoast. In spite of high temporal variability of the currents at most locations on the shelf, the standard errors of the estimates of the long-term (~30 month) means are such that qualitative direction is not in question for many of the locations. This suggests that the ultimate fate of freshwater from the Mississippi and Atchafalaya River sources is downstream toward Texas. However, as will be shown, many processes occurring at short time scales of days and weeks can interrupt and even reverse the inner shelf flow. Further, satellite observations show that the Mississippi and Atchafalaya River plumes are usually distinct and separated in space (Salisbury et al. 2004). Oey (1995), in a 3-D circulation numerical modeling study of the northern Gulf of Mexico using the Princeton Ocean Model, quantified the relative forcing of wind, buoyancy from the Mississippi and Atchafalaya River discharge, and offshore circulation features. He concluded that the westward flow over the inner shelf was due primarily to wind, and that motions associated with offshore circulation features and modulated by the wind curl primarily drove the flows elsewhere over the shelf. His peak fall transports over the inner shelf were 0.21 to 0.25 Sv (downcoast), with 40-48% being due to the wind forcing, 28-33% due to river discharge buoyancy effects, and 19-32% due to the offshore forcing provided by motions associated with Loop Current eddies.

Etter et al. (2004) constructed monthly mean heat budgets and seasonal mean freshwater budgets for the Texas-Louisiana shelf for the period May 1992 to November 1994 using the LATEX A hydrographic data (Nowlin et al. 1998) supplemented by meteorological data derived from a mixture of measurements and products from numerical models. The heat flux divergence, computed as a residual in the heat budget equation, exhibits strong and highly variable gradients at the shelf edge, particularly in regions adjacent to eddy activity. The freshwater flux divergence, computed as a residual in the freshwater budget equation, indicates a persistent divergence of fresh water over the study area in agreement with the baseline climatology. Filling and flushing times are balanced by reducing the westward-directed fraction of Mississippi River discharge to 47% versus the commonly assumed 53%, thus supporting the assertion that approximately half of the long-term Mississippi River discharge is directed westward upon entering the Gulf of Mexico.

In the Louisiana Bight region west of the Southwest Pass Delta and east of Mississippi Canyon, there exists a quasi-permanent anticyclonic gyre, first described by Ichiye (1960) and later by Wiseman et al. (1974), internal motions, and Wiseman et al. (1982), salinity and temperature variability, which is formed by the rotational modification of the Mississippi River plume as it exits Southwest Pass (Figure 4). The strength and position of the anticyclone is dependent on the strength and duration of local winds. Upwelling (eastward) winds favor the weakening of the gyre and the offshore displacement of the freshwater plume; conditions that occur more frequently in summer (Hetland and DiMarco 2006; submitted). Downwelling winds favor strengthening the gyre.

1.b. Scales of variability

Knowing the spatial scales at which processes operate provides important intrinsic information for measurement programs, numerical modeling studies, and in objective analysis schemes. The use of statistical methods to obtain characteristic length scales has a long and rich tradition in oceanography and meteorology. The most common use in meteorology is optimal interpolation, i.e., objective analysis, in which correlation scales are used to objectively map irregularly spaced observations to some type of regular grid (Gandin 1965). Bretherton et al. (1976) describe the use of correlation scales in the design of oceanographic experiments; other examples using real data include Sciremammano et al. (1980) and Denman and Freeland (1985).

Estimates of the spatial scales over the continental shelves east and west of the delta are given by Li et al. (1996) and DiMarco et al. (2006a; submitted). Cross-shelf scales over the western Texas-Louisiana shelf are about 15 km but are nearer 20 km over the eastern and central shelf. The central and eastern Texas-Louisiana shelf region is broad with gradual bathymetric gradients similar to the West Florida Shelf area. The western Texas Shelf has steeper topography, though not as steep as the western DeSoto Canyon region immediately east of the delta. The cross-shelf spatial scales of the Texas-Louisiana Shelf, therefore, show a significant relationship with shelf width. Li et al. (1996) use an empirical relationship, $m_t = m_o\left(\frac{L}{L_o}\right)^p$, to relate scale length, m_t, to shelf width, L. They found that: m_o = 12.1 km, p = 0.79, and L_o = 100 km gave the best fit to their scales estimates. Chen (1995) showed similar scales of variability while analyzing shipboard ADCP transects from the Texas-Louisiana Shelf. DiMarco et al. (submitted 2006a) show that this empirical relation also can predict the cross-shelf spatial scales on the West Florida and Mississippi-Alabama Shelves, data from nine cruises giving excellent agreement with predicted values. Using shelf widths of 90 and 235 km for the Mississippi-Alabama and West Florida Shelves, respectively, yields predicted cross-shelf scales of 11 and 24 km.

There is evidence from recent cruises from the spring and summers of 2004 and 2005 (DiMarco et al. unpublished) that the spatial and temporal scales of biogeochemical processes on the Texas-Louisiana Shelf in the hypoxic zone are of the same spatial and temporal order as the physical processes. For example, time series of stratification, as estimated from moored conductivity (salinity) sensors, at fixed depths above and below the nominal pycnocline at 10 m depth during spring/summer 2005, show strong coherence with dissolved nitrate/nitrite and dissolved oxygen concentrations below the pycnocline (Figure 5). Also, coastal current meanders associated with bathymetry variability west of Terrebonne Bay and south of Atchafalaya Bay and along the inner shelf (10-30 m depth) have been observed to affect the depth and strength of the pycnocline with alongshelf spatial scales of about 15 km. Beneath this depth-varying pycnocline, dissolved oxygen and nutrient concentrations were observed to co-vary in phase at the same spatial scales as the stratification (DiMarco et al., 2006b, in prep).

It is imperative therefore that sampling programs examining physical and biogeochemical processes on the Texas-Louisiana Shelf be performed at least at the scale lengths found for the physical processes. Sampling strategies that have larger sampling scales will undoubtedly alias the variance of the dominant processes, complicate interpretations, and may lead to faulty conclusions.

2. Forcing Mechanisms and Their Relationship to Hypoxia

In this section, we characterize the present understanding of the physical forcing mechanisms affecting the waters of the northern Gulf of Mexico and how they control the extent, severity, and duration of hypoxia of the Texas-Louisiana Shelf.

2.a. Wind forcing

The wind-driven quasi-annual pattern of low-frequency circulation over the Texas-Louisiana Shelf directly affects the local stratification. In summer during upwelling favorable conditions, the effect of the wind is to pool the freshwater discharge of the Mississippi and Atchafalaya Rivers over the eastern Texas-Louisiana Shelf and thereby enhance stratification. During the nonsummer downwelling conditions, the winds drive the currents downcoast, toward Texas, allowing the freshwater discharge to be transported away from Louisiana and weakening the stratification. Further, downwelling favorable conditions tend to press the coastal jet close to the coastline and intensify the coastal front. This would tend to weaken the pycnocline associated with the freshwater discharge, as the coastal jet becomes attached to the bottom, and weaken hypoxia. Based on this and the increase in thermal stratification in summer due to the peak insolation, it can be said that the quasi-annual pattern of circulation favors the development of hypoxia by intensifying summer stratification.

In addition, the severity and frequency of atmospheric storms and frontal passages increases in the nonsummer months (DiMego et al. 1976; Nowlin et al. 1998). The stronger winds break down the stratification through surface gravity wave breaking and shear mixing processes and promote mixing of oxygen-rich water to the bottom of the water column. In summer, the infrequency of atmospheric frontal passages allows stratification to remain established and inhibits the mixing down of oxygen-rich water. The seasonal pattern of storm occurrences reinforces the circulation pattern in promoting summertime conditions conducive for hypoxia formation. However, we note that although there is a robust seasonal pattern, there is considerable interannual variability in the timing and strength of the pattern owing to variability in the year-to-year forcing.

2.b. Freshwater input and river plume dynamics

The physical dynamics, geochemical transformations, and biological production of the north central Gulf of Mexico are profoundly influenced by the combined Mississippi-Atchafalaya River outflow, which annually discharges about 580 km^3 of water and introduces $210x10^9$ m^3 of sediment (Milliman and Meade, 1983) and $0.48x10^{12}$ moles total organic carbon (Trefry et al., 1994) into the Gulf. This discharge constitutes 10% of the total water mass on the Texas-Louisiana and Mississippi-Alabama continental shelves (Dagg, 1990) and 55% of the total freshwater input to the Gulf (Solis and Powell, 1999). While an additional 14 rivers discharge to the shelf between the delta and Brownsville, TX, their combined flow is an order of magnitude smaller than that of the Mississippi-Atchafalaya combined flow. However, heavy rainfall events in their catchments can produce greatly increased flow for periods of hours to a few days (Nowlin et al., 1998).

Of the two spatially separated components, the Mississippi River flow enters the Gulf of Mexico through the bird-foot delta and the Atchafalaya flow through Atchafalaya Bay near Morgan City, LA. The Mississippi River discharges onto the continental shelf via three large passes and numerous smaller channels along a 40 km peninsula at roughly 89˚W, 29˚N. The Atchafalaya River discharges into the 1500 km^2 estuarine system of Atchafalaya Bay at roughly 91.5˚W, 29.3˚N (Figure 6). The mean annual discharge of the Mississippi River at Tarbert Landing, LA, is approximately 13,500 m^3/s. A general summary of fluvial inputs shows 30% increase in river flow since the 1950s, the period when hypoxia has become intense (Carey et al., 1999), although the long-term mean since 1815 shows little change despite decadal variability (Turner and Rabalais, 2003). Wiseman et al. (1997) reported that there was strong correlation between the areal extent of hypoxia and Mississippi River discharge ($R^2 \sim 0.6$) during the years 1985-1996, however, that correlation is much poorer when numbers from the years 1997 through 2006 are included.

A critical factor concerning the volume of freshwater discharged onto the Texas-Louisiana Shelf is the control of diversions operated by the U.S. Corp of Army Engineers. Since the late 1970s, the ratio of freshwater exiting on to the shelf near Morgan City, LA, i.e., the Atchafalaya River, has been constrained to 30% of the total Mississippi-Atchafalaya discharge. A look at this ratio over the period 1929-1991 (Figure 7) shows a steady increase from 15% in 1929 to 30% in 1950, followed by a 30-year period of large seasonal fluctuation superimposed over an increasing trend that peaks in 1972. Beginning in 1976, the ratio is essentially 0.3 (30%) with some short-term variability. Because about 50% of the Mississippi's flow goes east (Dinnel and Wiseman, 1986; Etter et al., 2004), the consequence is that the discharges from the Atchafalaya River and from the Mississippi through the balize delta account for roughly equal portions of the freshwater budget discharged onto the Texas-Louisiana Shelf. This low salinity flow is usually confined to the inshore portion of the shelf, although there is frequently a separation between the flow from the Mississippi River and the Atchafalaya as well as the anticyclonic gyre with high salinity in the Louisiana Bight mentioned above (Figure 5). In a realistic numerical study of the circulation of the northern Gulf of Mexico using the Regional Ocean Modeling System (ROMS ; Haidvogel et al. 2000), Hetland and DiMarco (2006; submitted) also find the separation of the Mississippi and Atchafalaya River plumes.

Many studies have reported on the dynamics of river plumes, typically by separating the buoyant plume into dynamically defined regions (e.g. Garvine 1987; O'Donnell 1990; Yankovsky and Chapman 1997; Hetland 2005). Usually, the structure of the plume is broken down into four regions: the river region (characterized by a barotropic pressure gradient), the advection dominated near-field (where the Rossby number, the ratio of flow speed to the Coriolis effect, is greater than 1), the far-field, where forces external to the plume dominate, e.g., Coriolis effect, wind-driving, and offshore circulation interaction, and, lastly, the coastal current, far downstream of the plume. In a numerical study, Hetland (2005) relates these plume structures to vertical mixing processes such as entrainment shear mixing and wind mixing and showed that shear mixing is dominant in the advective near-field region, while wind mixing occurs throughout the plume but has the greatest effect in the plume structure just beyond the near-field. Rowe and Chapman (2002), hereafter RC, used similar reasoning to suggest that hypoxia on the continental shelf is controlled by competing biogeochemical mechanisms whose relative strength depends on the distance from the freshwater source. The region is divided into process zones as opposed to fixed geographical zones. Combining the concepts of dynamics and process zones, Hetland and DiMarco (2006) show in a numerical study that the structure of hypoxia on the eastern Texas-Louisiana Shelf could be controlled by the flow characteristics of the river plumes and that the biological processes controlling the hypoxia changes with the plume structure from east to west.

The amount of coupling between the dynamical plume regions and the biogeochemical process regions is currently not known. However, as Hetland and DiMarco (2006) suggest, the river and near-field regions may be closely associated with RC Zone 1, where river sediment loading and the associated chemical reactions between reducing compounds in the nearshore sediments are greatest (Morse and Rowe 1999; Rowe et al. 2001). Further away in the far-field, the sediment load drops and light penetration increases, corresponding to RC Zone 2. Here, there is enhanced phytoplankton growth fueled by high dissolved nitrogen concentrations ($N < 120$ μmol kg^{-1}, $Si < 200$ μmol kg^{-1}: Turner and Rabalais 1991; Hitchcock et al. 1997). In the coastal current and RC

Zone 3, dissolved nitrogen concentrations are very low at the surface, and hypoxia is principally controlled by the local stratification, which is highly dependent on both the local wind field and the amount of freshwater coming down the rivers.

Because these process and dynamical zones are not tied to a specific geographic region, they are free to move and develop according to the relative strengths of the governing physical processes controlling them. Further, the relative extent, and duration of the zones can also vary with the governing processes. In this way, at a time when river discharge is high and there are slight winds and no interacting offshore circulation features, Zones 1 and 2 may be relatively large in comparison to Zone 3. At another time, wind and offshore features may modify the plume structure allowing for Zone 3 to be relatively larger than Zone 1 or 2. How tightly or loosely the Zones and regions are coupled is a question for further study. Also, the processes associated with the dynamical regions are considered irreversible, i.e., near-field water can be converted to far-field water, but not vice versa. However, the biogeochemical processes occurring in RC Zones 1, 2, and 3 can occur anywhere on the shelf but in different relative importance. Therefore, quantifying the processes controlling the transitions is fundamentally important to understanding how the physical processes control the underlying biogeochemical processes.

As an example of how physical constraints of the plume system can affect the size and placement of the hypoxic area, we build upon the plume dynamics theory propounded by Yankovsky and Chapman (1997). This theory predicts important length scales associated with a buoyant coastal discharge. For a bottom-advected discharge, as in the Louisiana Coastal Current, the downstream transport will be confined to the width of the offshore density front, *W*. If this front is trapped at an equilibrium depth, h_b, then the transport, T_b, is approximately $0.5\ u_z\ h_b^2\ W$, where u_z is the vertical shear of the horizontal flow. (It is assumed that u, the horizontal velocity, is zero at the bottom.) The shear, u_z, is given by the thermal wind equations as $g\ \rho_y/\rho\ f$, where g is the acceleration due to gravity, ρ is water density, and f is the Coriolis parameter. This leads to the following estimate of the equilibrium depth, $h_b = \sqrt{(2\ T_b\ W\ \rho\ f/\ g\ \rho_y)} \approx \sqrt{(2\ T_b\ \rho_0\ f/\ g\ \Delta\rho)}$, where ρ_0 is a characteristic density and $\Delta\rho$ is the density difference across the coastal front. This equilibrium depth will mark the inshore edge of any hypoxic zone, since further inshore the water is confined within the moving Louisiana Coastal Current and will be of lower salinity and well-oxygenated.

Murray (1998) monitored numerous CTD sections across the Louisiana Coastal Current off the Atchafalaya during the LATEX B program, including storm-driven and tidal signatures which would be expected to test the general applicability of the theory. The observed depth at which the front intersected the bottom is compared with that predicted by theory in Figure 8.

Although the data set is of restricted size, the theory appears to represent an upper bound on the observed depth of the toe of the front. There was a clear linear relationship between the predicted and observed parameters when a strong salinity front was present (cross-frontal salinity differences of 7 or higher). The ratio of estimated to observed water depth at the toe of the front, when plotted against the cross-frontal salinity difference (Figure 9), indicates that the analysis does not produce acceptable estimates of the depth at which the front intersects the bottom when the estimated cross-frontal salinity difference is small. It is unclear, though, whether this results from inabilities of the theory to handle such situations or from difficulties in estimating the inputs to the theory in such weakly stratified situations. Estimating the cross-frontal salinity difference is a particular source of error because of the short spatial scales. Dynamical processes occurring at short time scales, particularly wind forcing and non-Fickian dispersion processes, are not accounted for by the theory and *must* influence the observed structure of the front. Furthermore, the theory describes a situation where the system is approaching steady-state, which is unlikely in practice.

It is intriguing, given the above issues, that the theory of Yankovsky and Chapman (1997) does as well as it does in predicting the depth of the coastal salinity front's toe. This implies a dynamical importance for the baroclinic pressure gradients associated with the buoyant discharge from the Atchafalaya River. Whether a similar relationship holds for the coastal current further upcoast and associated with the bottom-separated plumes discharged from the Mississippi Delta has not been tested, but the theory does indicate that there is the possibility of profound differences in the dynamical behavior at different regions of the river plume. These differences may lead to differences in the biochemical responses in those regions.

2.c. Offshore circulation features

Offshore circulation features also dramatically affect the extent, severity, and duration of hypoxia on the shelf through the exchange of mass, energy, and momentum and by modulating the low-frequency wind-driven circulation. The principal offshore forcing of the shelf regions of the northern Gulf of Mexico is presumed to be associated with the Loop Current and its associated eddies (Molinari et al., 1978; Nowlin et al., 2001; Sturges et al., 2005; Sturges and Evans, 1983). A synopsis of the general circulation of the Gulf of Mexico including the Loop Current eddy shedding frequency is given by Schmitz et al. (2005), while the general circulation based on surface drifters is given by DiMarco et al. (2005). Usually, the Loop Current only influences the currents on the outer edge of the eastern continental shelf directly through the process of Loop Current Eddy formation (as the Loop Current extends northward into the Gulf of Mexico it tends to shed an anticyclonic ring). Estimates of kinetic energy in the mesoscale band (periods of 10 to 100 days) of the spectrum, i.e., those attributed to mesoscale circulation features like eddies, show a variable spatial distribution on the Texas-Louisiana Shelf. Mesoscale band kinetic energy decreases from the shelf edge inshore (Nowlin et al. 2005). The shelf edge shows two regions of increased variance: the eastern region near Mississippi Canyon and the western region where the shelf takes a 90° turn from an east-west orientation to north-south. The latter region is commonly referred to as the eddy grave yard because Loop Current Eddies will frequently dissipate there.

The influence of episodic offshore circulation features is to disrupt the seasonal wind-driven circulation patterns over the shelf; this can result in the cross-shelf transport of mass and material. The timing of these events is decidedly non-deterministic, owing to the aperiodic nature of Loop Current intrusions into the northern Gulf, separation periods of Loop Current Eddies (Sturges and Leben 2000), the variability of their trajectories (Vukovich 1986), and the production of smaller-scale (order 50 km) cyclonic and anticyclonic circulation features as eddies interact with the Loop Current, other eddies, and bathymetry (Hamilton 1992). However, the influence of these events on the hydrography and hypoxia can be considerable. For example, if a Loop Current Eddy impinges on the eastern Texas-Louisiana Shelf in summer when winds are upwelling favorable and have pooled large amounts of freshwater over the eastern shelf, then a considerable fraction of that freshwater can be entrained into the offshore feature and transported directly into deep water and away from the shelf, as has been shown to happen east of the delta by Belabbassi et al. (2005). The stratification, nutrient and particulate loading, and subsequent primary production associated with that freshwater would then not be available to the shelf. See section 2.h for further discussion of cross-shelf flows observed using satellites.

The surface mixed layer of the waters of the deep Gulf of Mexico ranges from 15 m thickness in summer to about 70 m in winter (Nowlin et al. 2001). The surface mixed-layer is typically well oxygenated and of higher salinity than the shelf waters. [Note: A deep water dissolved oxygen minimum exists in the Gulf of Mexico at about 300 m depth and is associated with Subtropical Underwater of Atlantic origin (Morrison et al. 1983), but there is no evidence of this water having ever been upwelled in to the hypoxic region off of coastal Louisiana.] The surface waters of the deep Gulf may impinge onto the shelf and interact with stratified waters of the inner shelf, advecting oxygen-rich water to the oxygen-depleted water beneath the pycnocline. In this way, the offshore waters provide a reservoir of dissolved oxygen and most certainly contributes to the observation that hypoxia is rarely seen in water depths greater than 40 m on the shelf. The high dissolved oxygen concentration values of the outer shelf are clearly seen in the vertical section of Figure 1.

2.d. Tides and inertial currents

The influence of tides on hypoxia is believed to be relatively minor in comparison to wind, buoyancy, and offshore forcing. Tides influence entrainment (horizontal) and shear (vertical) mixing and in this way will contribute to the breakdown of stratification derived from the freshwater sources. Historically, the tides of the Gulf of Mexico are considered to be small relative to oceanic tides (Zetler and Hanson 1972). The character of tides is known to range from principally diurnal (one high and one low tide per day) to mixed diurnal (Marmer 1954). Reid and Whitaker (1981) showed in a model study that the principal semidiurnal M2 tide is a Kelvin wave that propagates cyclonically around the Gulf basin around an amphidromic point north of the Yucatan peninsula. The diurnal tides are principally driven by co-oscillating flow through the Florida Straits and the Yucatan Channel (Reid 1990; Kantha 2005). Kantha (2005) shows that tides of the deep Gulf are predominately barotropic due to tidal forcing being quasi-resonant with the natural modes of oscillation of the Gulf basin. Reid and Whitaker (1981) estimate this mode to have a period of 1.2 days; Mojfeld and Wimbush (1977) estimate this period from pressure records as 1.5 days. Semidiurnal constituents are often amplified on the shelf regions of the Gulf of Mexico (Clark and Battisti 1981).

DiMarco and Reid (1998) describe the principal tidal current constituents from 81 current meter measurements deployed on the Texas-Louisiana Shelf from 1992-1994. They found three dominant tidal constituents: K1, O1, and M2. Collectively, tides account for roughly 10 percent of the total variance in the 8- to 40-hour (inertial) energy band, although this percentage can increase to nearly 50 percent inshore. The variance in the inertial band is typically less than the variance associated with longer period motions attributed to wind forcing (weather band: 2-15 days) and mesoscale forcing (longer than 15 days). The northeast corner of the Texas-Louisiana Shelf, near Atchafalaya Bay, has the largest tidal constituents with maximum near-surface (3 m depth) current amplitudes of about 9 cm/s, while typical maximum near-surface tidal currents near the shelf break are between 1 and 2 cm/s, for each of the K1, O1, and M2 components. In general, tidal current amplitudes decrease in magnitude with depth and semidiurnal constituents are amplified more at mid-shelf locations than the diurnal constituents. Diurnal constituents are essentially in phase across and along the shelf; semi-diurnal constituents show clear westward phase propagation.

At this time, there is no quantitative estimate of the time scales associated with tidal mixing of the freshwater discharge of the Mississippi and Atchafalaya Rivers. However, it would be relatively easy to configure a numerical circulation model of the region, prescribe tidal constituents based on the findings of DiMarco and Reid (1998), and determine the affect of tides on the stratification and the distribution of freshwater on the shelf.

Inertial currents are known to exist widely in the ocean (Webster 1968) and are attributed to sudden changes of wind stress (Pollard and Millard 1970), tidal resonance (Knauss 1962), or bottom scattering of tidal energy (Hendershott 1973). On the Texas-Louisiana Shelf, inertial currents are driven mainly by the passage of atmospheric fronts and tropical storms and hurricanes (Nowlin et al. 1998). Chen et al. (1996) describe the spatial distribution of near-inertial energy on the Texas-Louisiana Shelf from current meter observations during spring and summer 1992. The amplitudes of inertial oscillations on the Texas-Louisiana Shelf can reach 15 cm/s for a weak frontal passage. After Hurricane Andrew, inertial oscillations exceeded 50 cm/s. Inertial currents of the Texas-Louisiana Shelf are typically surface trapped above the pycnocline (Chen et al. 1996, DiMarco et al. 2000). Therefore these strong inertial currents can certainly assist in breaking down the stratification through shear mixing, promoting the downward exchange of dissolved oxygen, and, thus, reducing hypoxia.

The Texas-Louisiana Shelf is influenced by a diurnal sea breeze due to differential heating and cooling of the earth and ocean (Hsu 1988). Sea breeze on the Texas-Louisiana Shelf peaks in amplitude during the summer months when few atmospheric frontal systems pass through the region (DiMego et al. 1976). The latitude of the shelf and the diurnal driving combine to produce a near-resonant response of the surface currents to the wind stress. The oceanic response to the sea breeze is to produce energetic 24-hour period current oscillations in the near-surface layers (Daddio et al. 1978, DiMarco et al. 2000). The 24-hour currents rotate anticyclonically and can reach 60 cm/s and represent the largest non-storm induced high-frequency currents on the shelf. These currents can persist for a week or more, as long as the driving diurnal sea breeze persists with uninterrupted phase. The sea breeze extends across the shelf into the deep Gulf and there is evidence to suggest the signal extends to the southern Gulf and Mexico. The oscillations are phase locked to time of day suggesting a connection to the daily cycle of heating and cooling. The 24-hr currents may also enhance sheer mixing across the pycnocline and reduce stratification, thus, lead to reduced hypoxia; though, this process has not been investigated experimentally.

2.e. Surface gravity waves

Surface gravity waves of the Texas-Louisiana Shelf are the result of local wind forcing and propagation of swell wave fields produced by remotely located storms. However, the limited fetch and overall size of the Gulf of Mexico basin limits the amplitude and period of waves, which are considerably smaller than those found in the open ocean or larger basins, e.g., the Atlantic Ocean. Surface waves can influence the formation, duration, and breakup of hypoxia on the Texas-Louisiana Shelf by reducing stratification through wave breaking and mixing and by entraining air into the surface and sub-surface layers. Typical wave conditions over the inner Texas-Louisiana Shelf (10-20 m depths) have mean significant wave heights of less than one meter with average periods of about six seconds (DiMarco et al. 1996; Figure 10). During the passage of atmospheric fronts, winds can produce significant wave heights that exceed 3 m with 10-second period, however, these conditions are short-lived and usually only last a day or two.

Intense winds during the passage of hurricanes and tropical storms break down stratification and mix the water column from the surface to the bottom. The effects of hurricanes and tropical storms on the size of the hypoxic zone has been reflected in a few of the mid-summer hypoxia cruises performed by the LUMCON group. It is generally thought that if a hurricane impacts the hypoxic zone early in the summer (July or early August), then the water column can restratify in a few days days and hypoxic conditions can be restored in about 10-14 (Rabalais et al. 1994).

During Hurricane Andrew in August 1992, wave conditions in 16 m depth on the eastern Texas-Louisiana Shelf south of Terrebonne Bay exceeded 9 m (DiMarco et al. 1995), although a revised estimate, which accounted for nonlinear wave-wave interaction, put the wave height closer to 7.7 m (DiMarco et al 2001). Wave heights exceeded two meters for roughly 24 hours centered on the passage of the eye of the storm (Figure 11). Salinity and temperature observations during the hurricane indicate that the water column was fully mixed to a depth of 60 m during the storm. Although there were no estimates of dissolved oxygen taken immediately after the storm, hypoxic conditions on the eastern Texas-Louisiana Shelf were probably eliminated. As this storm occurred late in the summer, hypoxia did not re-establish on the shelf as conditions unfavorable to hypoxia developed.

In contrast, during early July 2005, Hurricane Cindy passed over the eastern Texas-Louisiana Shelf making landfall near Fourchon, while less than one week later Hurricane Dennis passed through the eastern Gulf of Mexico making landfall on the Florida panhandle near Pascagoula. The outer storm bands of Dennis reached the eastern Texas-Louisiana Shelf. In May 2005, hypoxia was found in the near bottom water of the eastern Texas-Louisiana Shelf from the Southwest Pass delta region to south of Cameron, LA (Figure 12). After the passage of the July hurricanes, no hypoxia was found east of 92.5°W. West of this location, where storm winds and wave action were considerably weaker, hypoxia and anoxia were found to the Texas-Louisiana border. By mid-July, the NOAA-NMFS SEAMAP fisheries cruise showed low dissolved oxygen concentrations returning to the eastern shelf. By month's end, Rabalais reported hypoxia had been re-established across the whole of the eastern portion of the shelf from Southwest Pass to Cameron, LA (Figure 4 in Rabalais et al., 2006). Thus, the effects of even large hurricane waves may be only temporary if the storm occurs early in the season and with time for stratification and other hypoxia favorable conditions to develop.

2.f. Relationship of stratification and dissolved oxygen concentration

In Section 1, water column stratification was shown to be a necessary but not sufficient condition for hypoxia to occur in coastal water, i.e., stratification must be accompanied by metabolism of organic material below the pycnocline. While stratification is dependent on both temperature and salinity differences between surface and lower water layers, over the Texas-Louisiana shelf freshwater discharge is generally highest in late spring, while temperature exerts its greatest effect in summer (Nowlin et al. 1998, Etter et al. 2004, Dinnel and Wiseman 1986); thus, peak stratification generally occurs in the summer. Once stratification has occurred, the balance between respiration and photosynthesis, along with atmospheric transfer and local advective processes, controls the dissolved oxygen concentration of the water column. In addition to water column stratification, which inhibits mixing of dissolved gases across the pycnocline, biological and chemical processes, e.g., microbial respiration and reduction, must also be present to draw down oxygen levels. Dissolved oxygen concentration levels on the eastern Texas-Louisiana Shelf have been shown to drop from saturated to hypoxic levels in about 10-14 days (Rabalais et al. 1994; Rabalais et al. 2006).

Belabbassi (2006), in a reanalysis of historical data on the eastern Texas-Louisiana Shelf showed a significant correlation in summer between Brunt-Vaisala (BV) frequency and near-bottom dissolved oxygen concentration. She found that hypoxia was not found at Brunt-Vaisala frequencies less than 40 cycles/hour. Further, her investigation included the entire northern Gulf of Mexico including the western Texas-Louisiana Shelf and the northeastern shelves of the Mississippi-Alabama Shelf and the West Florida shelf. She found that BV frequencies greater than 40 cycles/hour were extremely rare outside of the eastern Texas-Louisiana Shelf, intimating that the absence of strong stratification on these shelves contributed to the rare occurrences of hypoxia there, despite similar values of benthic respiration across the northern Gulf shelves (Rowe, personal communication).

2.g. Topography and alongshelf density variability

The Louisiana Coastal Current, which follows along the inner shelf of coastal Louisiana, is predominately a buoyancy-driven current that is modified by winds. Wiseman et al. (2003) have shown that south of Terrebonne Bay, the current is essentially east-west with frequent direction reversals, and two-layered with opposite phase above and below the pycnocline. Often the layers are decoupled, presumably when stratification is high.

The local bathymetry of the inner eastern Texas-Louisiana Shelf has many shoals, particularly along the 10-15 m isobaths and west of Terrebonne and south of Atchafalaya Bay. The shoals produce current meanders along the inner shelf. Because of the intense salinity gradient across the current, the current meander can produce large variations in the density field along the inshore (10-30 m) isobaths (DiMarco et al., 2006b; see also Section 2.h). The along-shelf variability of the inner shelf density field was observed west of Terrebonne Bay during seven cruises within the hypoxic zone in 2004 and 2005. The variability of the density field was reflected in the distribution of hypoxia and other chemical properties (DiMarco et al., 2006b). Generally, the wave-like patterns in the along-shelf density field can have up to 10 m amplitude (crest to trough) in 20 m total water depth and wavelengths of roughly 50 km (Figure 13). The most striking feature is that near-bottom dissolved oxygen concentrations vary with the crest and troughs of the density structures as the variability in stratification oscillates from strong to weak (DiMarco et al., 2006b). Winds can affect the location of the current meander, producing complex and dynamic behavior of the hypoxia field.

The current meander observed in August 2004 can be frequently seen in the historical record of archived satellite sea surface temperature and true color imagery (e.g., March 2001, October 2005) leading to a conclusion that the formation of the meander is common. Glenn et al. (2004) have observed topographic features off the New Jersey inner shelf that are similarly collocated with historical regions of low dissolved oxygen.

2.h. Satellite observations of shelf and cross-shelf flows forced by winds and eddies

As stated above, the outer regions of the Louisiana-Texas shelf are influenced by intrusions of the Loop Current and detached eddies. The frequency with which these deep ocean features, characterized by strong velocity fields, influence the shelf varies over both time and space. Continuous thermal infrared (sea surface temperature) satellite surveillance of the Louisiana-Texas continental shelf, slope, and rise during the 1992-1994 Louisiana-Texas Physical Oceanography Program (Walker et al., 1998) revealed several locations in the northwest Gulf where large masses of shelf water moved off the shelf into deeper water. Two of the fifteen major cases identified within the three year period, in October 1992 and November 1993 (Figure 14), involved large buoyant flows of the Mississippi River plume, but in all cases the off-shelf advection of water could be attributed to warm core eddies or warm/cold core eddy pairs. The October 1992 Mississippi plume "jet" flow described in detail in Walker et al. (1996) was initiated by strong northeasterly winds associated with the passage of a tropical storm system east of the Mississippi Delta. Subsequent to the development of this jet flow, with maximum velocities of 100 cm/s, an estimated 14,000 km^2 of river and shelf water was entrained seaward along the eastern flank of a warm core eddy, resident in the northwest Gulf (Figure 14, left panel). In November 1993, approximately 16,000 km^2 moved off shelf directly seaward of the bird-foot delta. This feature was 200 km long and 100 km wide, with an estimated velocity of 34 cm/s (Figure 14, right panel).

The launch of the SeaWiFS ocean color sensor in August 1997 advanced capabilities to detect river water away from major source regions within the northern Gulf. In particular, chlorophyll a algorithms, based on the 490/555nm band ratio, provide an effective means of tracking the movements of pigment-rich river and shelf water, especially when entrained seaward into the relatively pigment-poor Gulf waters (Muller-Karger et al., 1991; Walker et al., 2005). The main sources of pigments in these waters are chlorophyll a and colored dissolved organic material (CDOM; Carder et al., 1989). Using SeaWiFS data, Yuan et al. (2004) demonstrated that eddies generated by hurricanes and tropical storms entrain significant amounts of the Mississippi River's dissolved organic carbon (DOC) into the oligotrophic Gulf. Assuming a plume depth of 10m, they estimated as much as 5.4 x 10^{11} g DOC, or more than 25% of the Mississippi River's annual DOC flux, may have moved across the shelf after Tropical Storm Barry in 2001 over a 2-week period. Similarly, a prominent flow of combined river and coastal water was observed after Hurricane Ivan passed east of the bird-foot delta in September 2004. The SeaWiFS image of 19 September, 3 days after Ivan's passage, revealed a filament of pigment-rich water extending southeastward from the bird-foot delta that became entrained between a warm- and cold-core eddy (Figure 15). Superimposed on this chlorophyll a image is the track of NDBC meteorological buoy 42040 which broke free from its mooring when the eye of Hurricane Ivan passed over it. The buoy's motion revealed the presence of a swift current which initially flowed southwestward towards the bird-foot delta and then turned to the southeast near the 1000m isobath. The details of this event can be found in Walker et al. (2005) and Stone et al (2005). Episodic seaward flow events such as these serve to reduce the nutrient and freshwater loading on the shelf areas both east and west of the delta.

Significant seaward fluxes of river water, inorganic and organic sediments, and nutrients are also characteristic of the approximately 20-30 winter storms which impact the Louisiana and north Texas coastal regions each October-March period. These weather systems are accompanied by strong winds blowing from the west and northwest, which drive the buoyant river plumes to the southeast. During these events, Mississippi River water is dispersed into deep water (Walker et al., 2005), whereas the Atchafalaya plume is dispersed onto the shelf between the two deltas (Walker and Hammack 2000) (Figure 16-top). The west winds associated with these winter storm events are fairly short-lived (1-2 days), however, and the river water soon resumes its more normal flow to the west towards Texas (Figure 16-mid and bottom). Under conditions of moderate easterly winds, typical of spring, river water is trapped against the coast and on the shelf (Hitchcock et al. 1997; Walker et al. 2005). The synchronous timing of this wind regime and river flooding can produce large-scale phytoplankton blooms such as is shown in Figure 17 (from Walker and Rabalais 2006).

During summer, the Mississippi plume is often driven to the east and southeast by the prevalence of winds blowing to the east for about 6 weeks (Cochrane and Kelly 1986; Nowlin et al. 1999; Morey et al. 2003; Walker et al. 2005). In addition, occasional intrusions of the Loop Current and large eddies influence the flow field near the delta headland. The proximity of the shelf edge to the delta headland and the presence of the deep De Soto Canyon east of the delta increase the likelihood of seaward entrainment of river water into the deep Gulf as is shown in Figure 18. During summer, a reduction in nutrient loading to the Louisiana shelf from river discharges at the bird-foot delta can be expected; however, the summer wind regime forces the Atchafalaya River plume onto the shelf between the two deltas. Not surprisingly, the region between the two deltas has been shown to experience the most extreme and frequent conditions of hypoxia (Rabalais et al. 2002).

Clear-sky SST imagery, coincident with the May 2005 cruise (Figures 12-top and 13), revealed the presence of surface temperature structures suggestive of shelf waves with wavelengths of 70 to 90 km between the two deltas (Figure 19). It is of interest that this image also reveals the presence of warm water from a large warm-core eddy of the Loop Current in close proximity to these wave-like features. The warm-core eddy had recently moved close to the Louisiana shelf (i.e., warmest waters in Figure 19). The warm water is clearly seen elevating the pycnocline between 90°W and 90.5°W in the vertical section along the 20-m isobath shown in Figure 13. One possible source of energy for the generation of shelf waves on the Louisiana shelf is the eddy field along the outer shelf. These preliminary observations indicate that the impacts of the offshore eddy field on shelf hypoxia warrant further study. Recent numerical investigations by

Kiselkova et al. (personal communication) have revealed the presence of wave-like features on the Louisiana shelf between the two deltas that may disrupt hypoxia, at least temporarily. The cause of these waves has not yet been clearly determined.

A disadvantage of satellite observations is their inability to observe the subsurface layers of the ocean. During August 2005, we observed south of Atchafalaya Bay a complex layering of inshore and offshore waters that indicates a combination of local and remote driving of observed low dissolved oxygen concentrations at near bottom and at mid-water depths (Figure 20). The near bottom low-oxygen layer is believed due to local benthic decay processes. However, the mid-water low-oxygen layer was found to be produced remotely and inshore and was characterized by high nutrient concentrations, low light transmission, high fluorescence, and relatively high salinity. Total water depth in the area was about 20 m and the mid-water low-oxygen layer was at 10 m depth. The layering was distinct, stable and persisted for at least four days, the duration of sampling in the region (DiMarco, unpublished data). The mid-water layer had enhanced primary production relative to other layers owing to the high nutrient concentrations. Cross-shelf sampling revealed that the mid-water layer was found attached to the bottom further onshore and to be actively advecting hypoxic, nutrient-rich, near bottom water seaward along a density surface. The source of the nutrients is believed to be through the remineralization of organic decay products rather than direct nutrient loading from the river sources. This therefore represents a mechanism for remineralized nitrogen to contribute to primary production further offshore. The organic material will ultimately flux to the ocean bottom and provide material for microbial decay processes and presumably, under the right conditions, hypoxia. This mechanism can be of considerable importance in driving the observed seasonal hypoxia, particularly in low river discharge years, as was the case in 2005. However, the frequency at which this process occurs is not known.

3. Potential Effects of Global-scale Climate Change on Hypoxia of the Northern Gulf of Mexico

There is almost universal agreement among climate scientists that there have been global scale changes in the earth’s climate during the last one hundred years (IPCC 2001). The effects range from global warming, to a decrease in sea ice coverage extent, sea level rise, and increased ocean heat content, to name but a few. The future effects of these changes on humans and the environment are areas of intense research. It is not the purpose of this section to provide definitive answers about the effect of global scale climate change on hypoxia. Rather, the intent is to provide some thoughts on some possible consequences of global warming on the physical oceanography of the Texas-Louisiana Shelf. We consider three potential changes: basin scale wind patterns, thermohaline circulation, and precipitation over the Mississippi River drainage basin.

3.a Large-scale changes in wind forcing patterns

Global wind patterns are controlled by the exchange of heat energy between the tropics and the poles. The seasonal cycle of wind forcing in the Gulf of Mexico will likely be affected by a change in global wind patterns. Presently, along shore winds on the Texas-Louisiana Shelf control the establishment and direction of the Texas Coastal Current and the Louisiana Coastal Current. The coastal currents typically flow downcoast in most of the year (September through May) and reverse during the summer. It is not known what if any changes to the timing and strength of the annual pattern of wind fields over the Gulf will occur. However, if along shore winds do not reverse in the summer months, one can expect that the pooling of freshwater south of Louisiana will be strongly diminished or not occur at all. Freshwater will then likely extend further downcoast into Texas coastal waters. Salty oxygen-rich surface waters from the Mexican shelf will also not be brought northward into Texas. The result of this may be that hypoxic conditions may extend further downstream from the river sources and occur more frequently into Texas. However, under this scenario, the eastern Texas-Louisiana Shelf will not experience the pooling of freshwater and one would expect hypoxia to be confined close inshore and associated with the coastal jet of the river plume. Hence, there may be less hypoxia on the Louisiana Shelf.

If upwelling conditions become more frequent due to changes in wind forcing patterns, freshwater discharge may be forced further offshore making it more susceptible to entrainment into offshore circulation features. In this scenario, hypoxic conditions may become less severe due to the transport of surface production into the deep Gulf and the reduction of stratification due to less freshwater on the inner and mid-shelf.

Some investigators have reported that some global warming scenarios will lead to more frequent and intense hurricanes (Emanuel 2005). The obvious affect of more hurricanes is an increased likelihood of hurricanes impacting coastal Louisiana, which would temporarily mix shelf waters and reduce hypoxia.

3.b. Climate-induced changes to the Loop Current System

Bryden et al. (2005) published a landmark paper describing the reduction of the meridional overturning of the Atlantic Ocean by 30% during the last 20 years. Although they do not predict how this reduction will affect the Gulf stream system of the Atlantic, it is interesting to note that direct observations of the transport through the Yucatan Channel during 1999-2001 (Shienbaum et al. 2002), show a significant decrease as compared to earlier transport estimates (Gordon 1967, Roemmich 1981) by about 25%. A reduction in the transport through the Yucatan Channel, likely means a reduction in the Gulf Stream System transport. If this reduction is related to the meridional overturning of the Atlantic Ocean and the reduction continues, it is reasonable to assume that the statistics of the Loop Current System will be affected in some way.

Whether there are more or fewer Loop Current Eddy shedding events or more or less frequent northward penetration of the Loop Current onto the northern shelves is open to speculation. However, more frequent interaction of the Loop Current (and its eddies) will likely reduce the amount of freshwater discharge from Southwest Pass to the Texas-Louisiana Shelf. Presumably, this will reduce the intensity of stratification (all other forcings being equal), the amount of nutrient loading, and the amount of primary production on the shelf. Hypoxia may therefore be less severe or limited to areas close to the river delta. If there are fewer impingements of the Loop Current System, then more freshwater from Southwest Pass will be available to the shelf. This may lead to more intense stratification, increased nutrient loading, and more primary production. This would then tend to favor more extensive and severe hypoxia on the Texas-Louisiana Shelf.

3.c Climate-induced changes in Mississippi River basin drainage and discharge

Decadal scale variability of rainfall in the Great Plains regions of the United States has been linked to major climate indices, e.g., the Pacific Decadal Oscillation and El Nino – Southern Oscillation (ENSO). The quantification of the effects of global warming on these indices is ongoing (see e.g., McPhaden 1999; McPhaden et al., 2006). To date, there has been no specific investigation of the effects of global warming on precipitation in the Mississippi River drainage basin, so again we can only offer speculation. The effect of increased precipitation will be to increase the stratification (but not necessarily the nutrient loading) on the shelf and inhibit downward mixing of surface oxygen-rich waters through the pycnocline. In this scenario, we would expect hypoxic conditions on the shelf to worsen. With less precipitation, both nutrient loading and stratification will likely be reduced, leading to less severe hypoxic conditions.

Of course, the three scenarios presented above of the potential affects of climate change on hypoxia are simplistic. It is likely that all three effects may occur simultaneously or in some combination and that they may enhance or reduce the effect of one another. For example, if river discharge decreases and Loop Current interactions with the shelf decrease, hypoxic conditions may not change at all from present values. Conversely, if river discharge increases and Loop Current interactions decrease, hypoxic conditions may worsen more than if river discharge alone increased.

4. Knowledge Gaps and Recommendations

Although the basic processes of the physical oceanography of the Texas-Louisiana Shelf are fairly well documented, little is known about the relative strength and the temporal/spatial variability of each process on dissolved oxygen concentration in the water column and the sediments and the temporal/spatial variability of these relative strengths. Recent work in the region is shedding insight on how the physics and biogeochemistry are related. Yet several questions remain, including:

- How do transformation and transports associated with the Atchafalaya discharge differ from those of the Mississippi River Delta?
- How often does Mississippi-Atchafalaya related-hypoxia extend into Texas waters?
- What are the frequency of occurrence and spatial extent of hypoxic episodes east of the delta?
- How does the transport of fine sedimentary material affect hypoxia, and what controls the transport?
- What is the role of bottom boundary layer in controlling hypoxia? Are the mechanisms occurring in the bottom boundary layer different in the eastern and western hypoxic regions?

Many of these questions can be addressed by a combination of targeted field-oriented process studies and complementary numerical modeling studies designed with the appropriate spatial and temporal sampling frequencies. Despite the multitude of oceanographic observations in this region, there have been woefully few shelf-wide studies specifically designed to investigate the processes that control hypoxia. The comprehensive physically-oriented LATEX Study (Nowlin et al. 1998) did not deploy moored dissolved oxygen sensors nor was the hydrographic component of that program designed to study hypoxia. The LATEX data set, however, is an unmatched resource for numerical model initialization, skill assessment, and validation.

Clearly, a necessary step to unwrap the complexities of the processes that are encountered on the Texas-Louisiana Shelf is improved general circulation numerical modeling efforts. As previously stated, local wind forcing can have a profound effect on the structure and duration of hypoxia on the shelf. Because local weather is notoriously difficult to predict just a few days in advance and impossible to predict months or years in advance, these models should likely be run with a range of weather scenarios to produce a distribution of possible outcomes of hypoxic area for a given discharge, since discharge on the shelf takes about a month to emerge into the Gulf after being measured at the Tarbert Landing gage station. The complex circulation model described in Hetland and DiMarco (2006), though a useful research tool, only parameterizes the biological processes of the shelf in a simple way. To fully represent the complexities of the biogeochemical processes known to occur on the shelf, NPZ (nutrients-phytoplankton-zooplankton) type modeling (Fennel et al. 2005) must be included in future efforts to account for nutrient dynamics as well as dynamic sediment modeling that accounts for accumulation and remineralization of organic matter at the bottom and allows organic matter to be resuspended by bottom boundary layer. Presently, there are efforts underway addressing these issues.

Previously, predictive modeling efforts, such as those postulated by Scavia et al. (2003), have treated hypoxia on the Louisiana shelf as a low oxygen plume emanating downstream from the river source. The success of this model in hindcast mode comes at a high price in that the so-called “advection” term parameterizes all of the oceanic processes described in this paper into a single term having units of velocity and assumes a steady state. The actual coastal ocean is far from steady state, nor is it stationary, which is likely the reason that this model performs poorly in forecast mode when the advection term must be tuned using Monte Carlo methods. Further, although the advection term in this model is understood in a steady state context, it is conceptually displeasing that the exceeding small magnitude of advection (order 0.5 km/day) indicates that it takes more than a year for the drift to go the roughly 300 km from the Southwest Pass Delta to the Texas border. Therefore, the model may be describing next year's hypoxia rather than that of the present year.

Monitoring methods of the hypoxic area at the time of this writing were confined to a single shelf-wide monitoring cruise, made in late July of each year. Though this cruise has produced valuable insight to the understanding of hypoxia formation, the poor temporal resolution (once per year) and large spatial resolution (50 km spaced north-south survey lines) means that many of the oceanic processes, both physical and biogeochemical, known to exist on the shelf are not adequately resolved. It is recommended that in addition to the shelf-wide survey, high-spatial resolution process studies should also be conducted across the region to quantify the relative contributions of the biogeochemical processes with respect to the dynamical regions of the shelf. These cruises should also last on the order of the temporal scale it takes for the lower water column to go hypoxic (about 7 to 10 days) in order to fully describe the hypoxic process.

A network of real-time monitoring systems positioned at key locations across the region will assist in monitoring efforts, bring broad spatial and temporal context to process cruises, and provide coastal managers timely information to make relevant and informed decisions.

We note that this paper does not specifically address particulate and sediment dynamics. Issues such as particle flux, resuspension, and fluid and mobile muds have been studied in Atchafalaya Bay and delta region and the inner Louisiana Shelf (Adams et al. 1982; Allison et al. 2000; Gordon et al. 2001), however, there are relatively few data on the broader shelf region including the hypoxic region west of 92°W. The coupling of processes in the bottom boundary layer to the dynamical regions described earlier is also not known and should also be set as a high research priority.

5. Summary

There are many physical processes that occur on the Texas-Louisiana Shelf that affect the spatial distribution and temporal variability of freshwater and biochemical material. Some of the processes can enhance and strengthen stratified conditions on the shelf, thus are hypoxia-favorable, while other processes tend to weaken and reduce stratification and are hypoxia-unfavorable. The physical processes have a wide range of temporal (seconds to years) and spatial scales (meters to tens of kilometers) The relative timing and strengths of the physical processes can often produce complicated responses on the shelf that can vary spatially and temporally. The general pattern of low-frequency shelf circulation, peak summer insolation, infrequent atmospheric frontal systems in summer, weak tides, peak spring river discharge and nutrient loading all favor the development of summer hypoxia on the shelf. There is strong evidence to suggest that the surface plumes of the Atchafalaya and Mississippi Rivers are typically two spatially distinct systems. The physical and biochemical processes occurring within each system therefore have different roles and maintain and control hypoxia differently in each region. In the region closest to the Mississippi River delta, water column stratification is less a control on hypoxia than nutrient loading and water column respiration. However, south of Atchafalaya Bay, water column stratification is the dominant controlling mechanism for hypoxia, while nutrient recycling and remineralization and benthic processes seem more important that primary production and surface nutrient dynamics. Quantifying the relative roles of these processes in the different regions of the shelf should be regarded as the least known aspect of hypoxia research on the shelf and should be set as the highest research priority.

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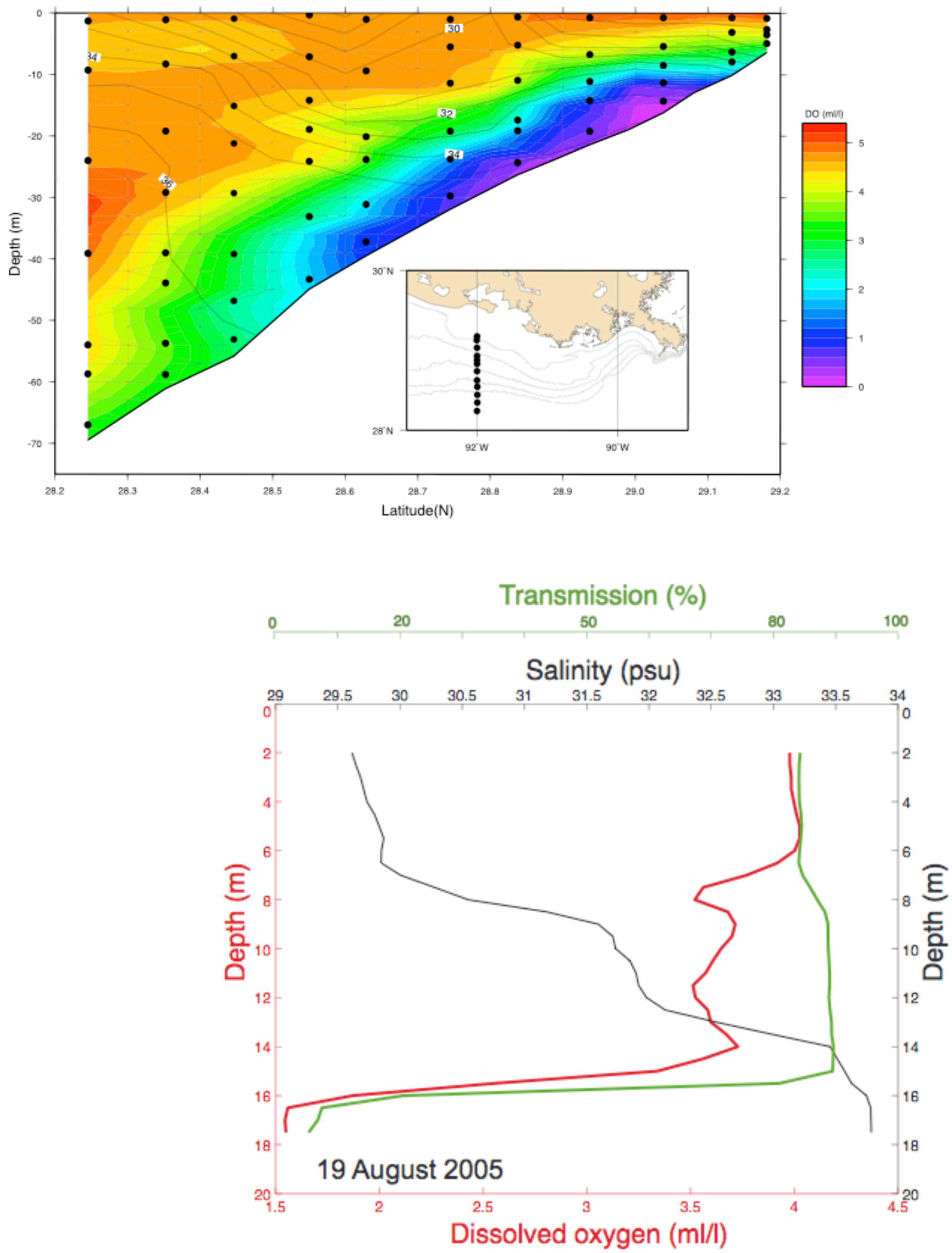

Figure 1. Top: Vertical section of dissolved oxygen concentration (color) and salinity (black lines) along cross-shelf transect south of Atchafalaya during LATEX July-August 1993 cruise. Inset shows geographical locations of stations and 10, 20, 30, 40, and 50 m isobaths. Bottom: Vertical profile of salinity (black), dissolved oxygen concentration (red) and light transmission (green) from a station located south of Cameron, LA on 19 August 2005. Note the oxycline coincides with a dramatic reduction of light transmission.

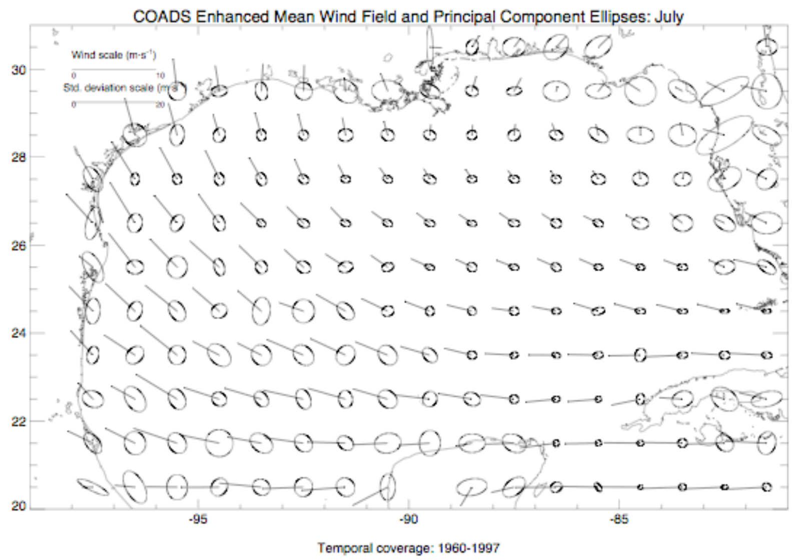

Figure 2. Mean wind field and principal component variance ellipses during July over northern Gulf of Mexico based on COADS data 1960-1997.

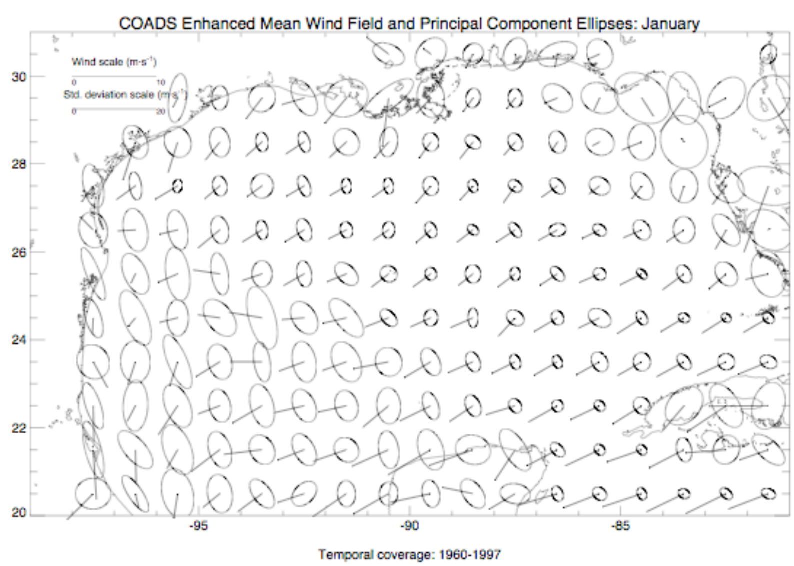

Figure 3. Mean wind field and principal component variance ellipses during January over northern Gulf of Mexico based on COADS data 1960-1997.

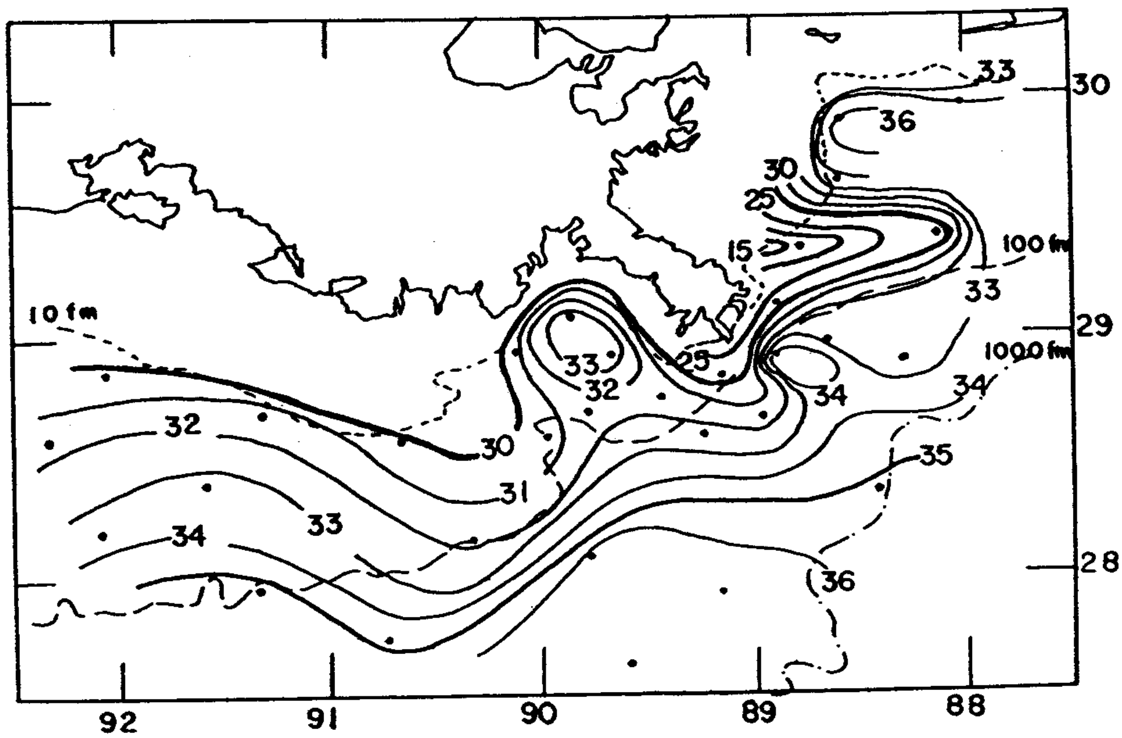

Figure 4. Surface salinity (o/oo) in Louisiana Bight area of eastern Texas-Lousiana Shelf, July 1955 (from Ichiye 1960).

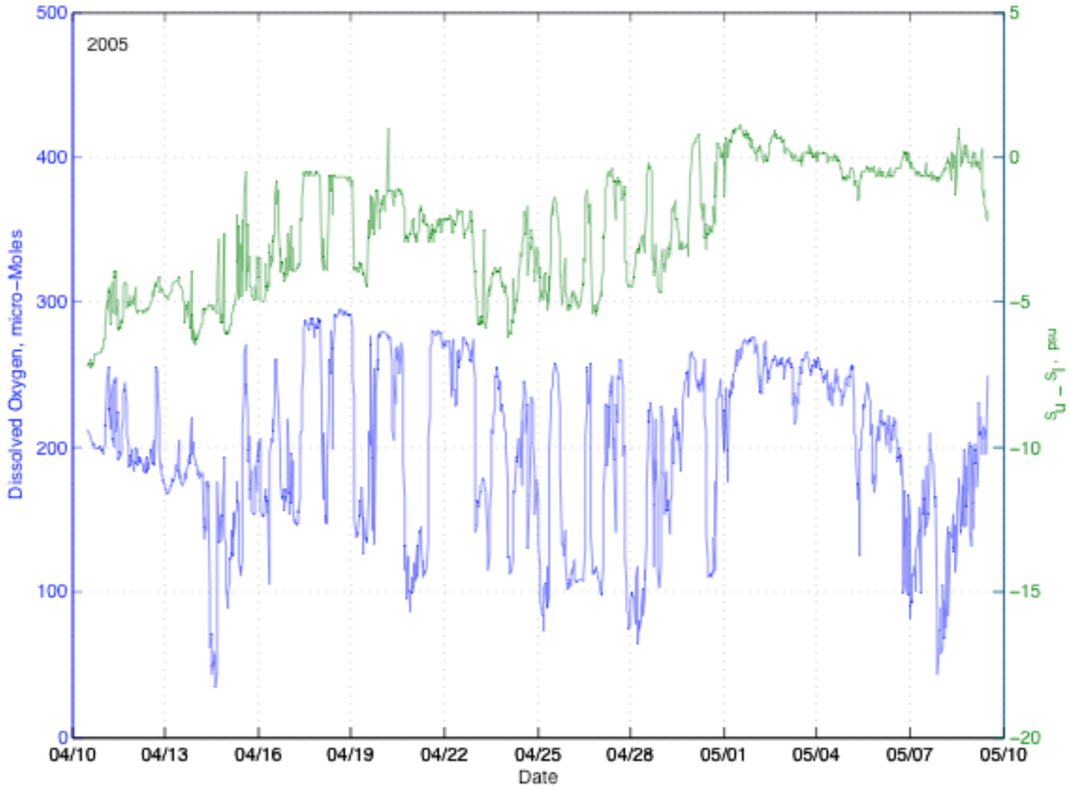

Figure 5. Time series of conductivity (salinity) difference (green) between sensors placed at 8 m and 14 m below the surface and dissolved oxygen concentration (μmol/l; blue) at 14 m depth at a location south of Atchafalaya Bay (29°N, 92°W), in Spring 2005.

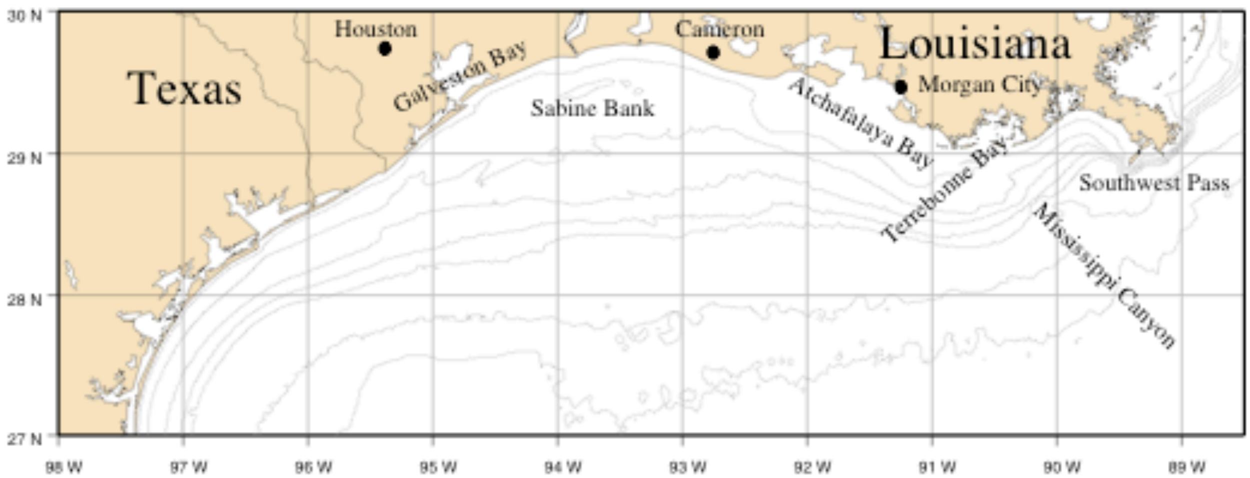

Figure 6. Texas-Louisiana Shelf region of northern Gulf of Mexico showing geographic locationsidentified in text. Bathymetry contours shown are 10, 20, 30, 40, 50, 200, and 1000 m.

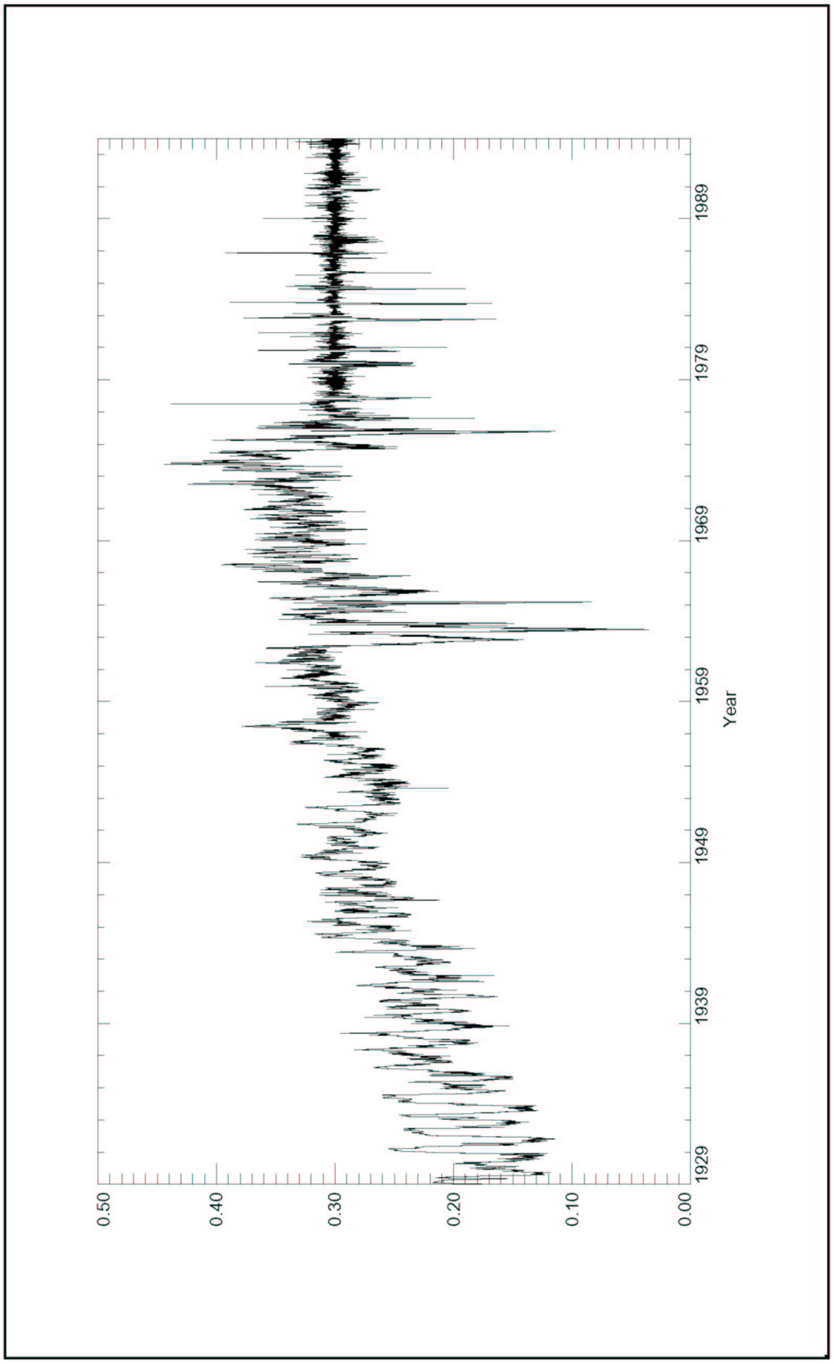

Figure 7. Long-term ratio of combined Mississippi-Atchafalaya River discharge to Atchafalaya River discharge 1929-1991. Note the leveling of the ratio beginning around 1978. (from Nowlin et al. 1998).

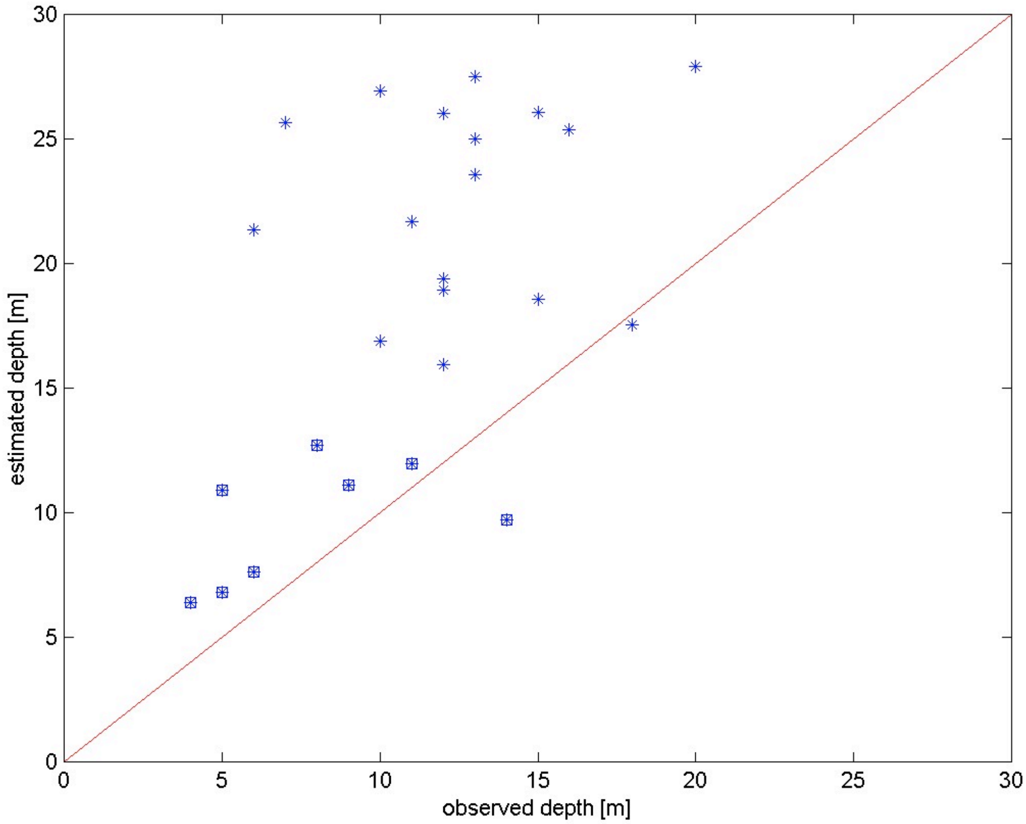

Figure 8. Comparison of the observed depth where the coastal front intersects the bottom with that predicted by the theory of Yankovsky and Chapman (1997) for 25 sections collected during LATEX-B (Murray, 1998). A line with unit slope is overlain on the data. Data points indicated by a square surrounding an asterisk are from sections where the cross-frontal salinity difference is estimated to be at least 7.

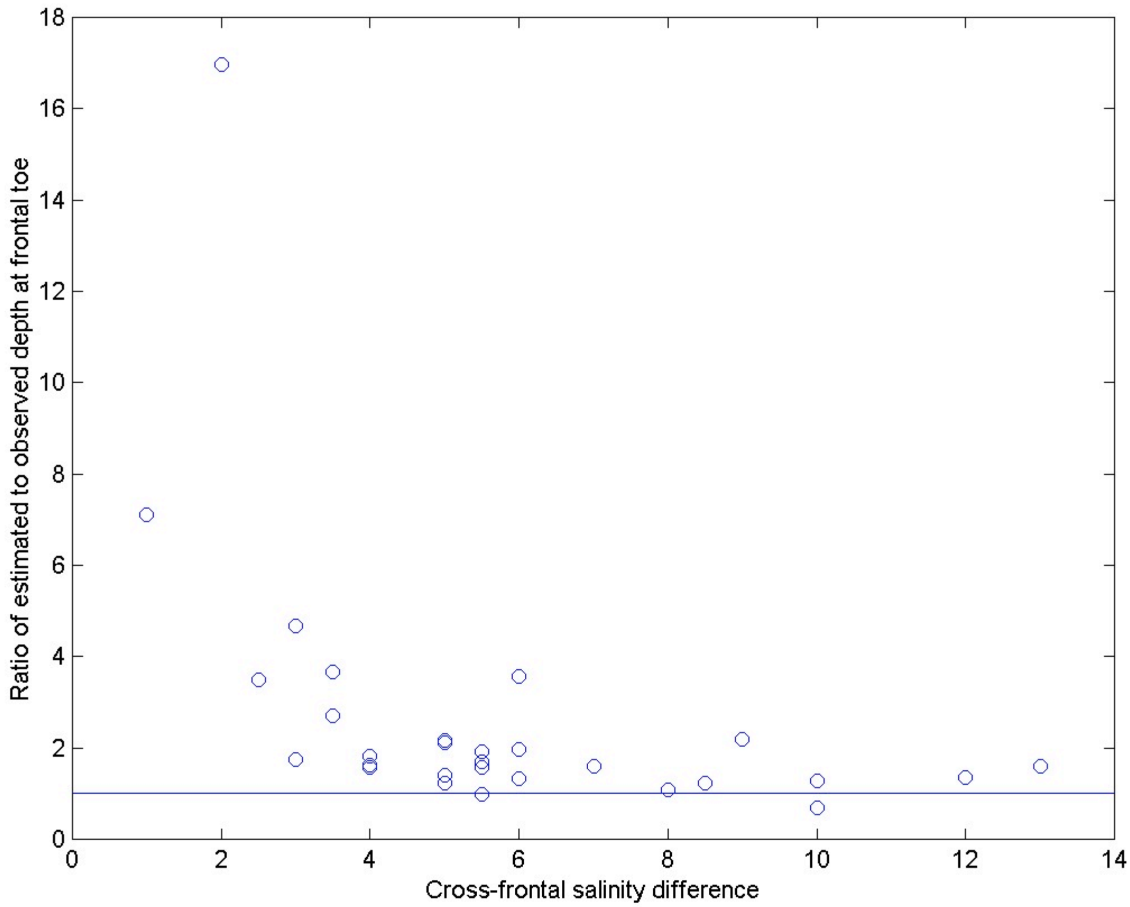

Figure 9. Plot comparing the ratio of water depth at the toe of the salinity front versus the cross-frontal salinity difference for 29 sections west of the Atchafalaya River mouth collected during LATEX-B cruises.

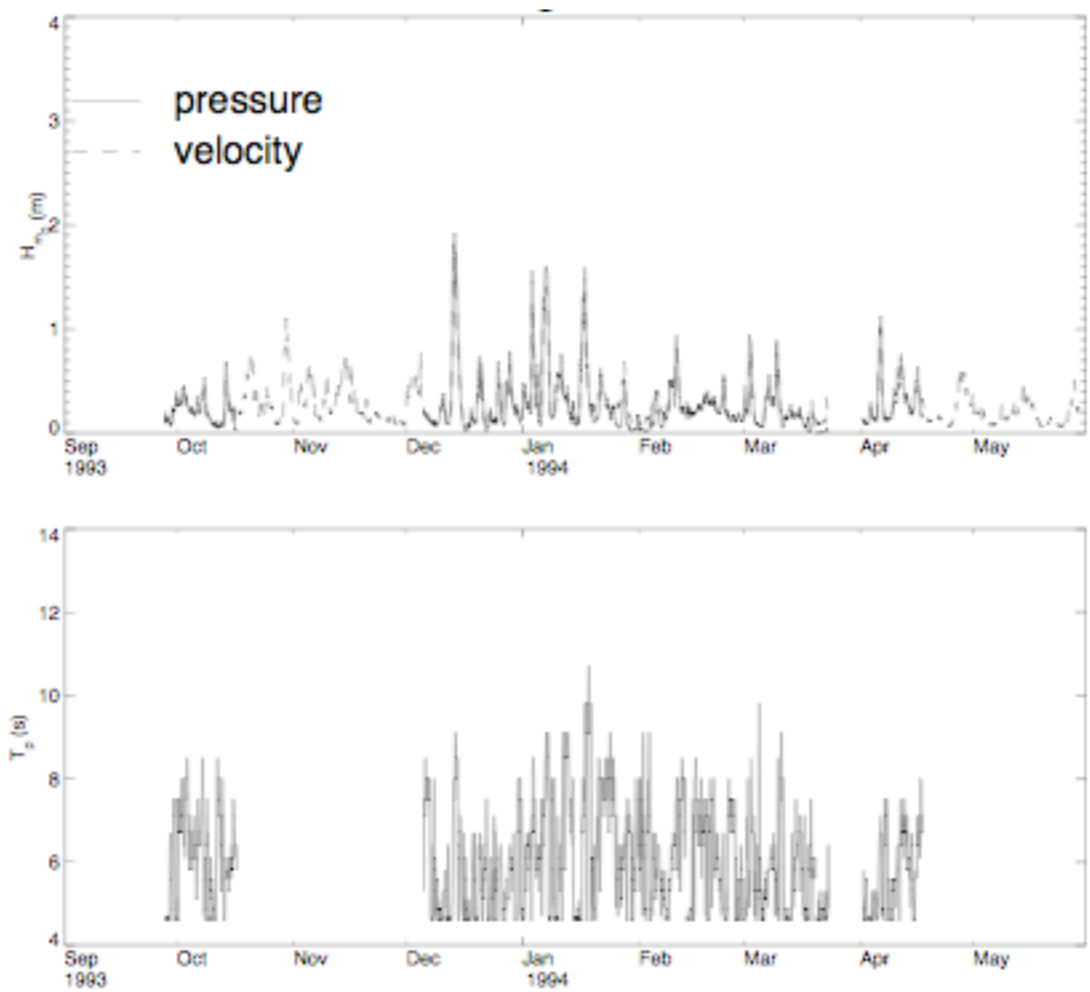

Figure 10. Significant wave height (top) and average wave period (bottom) estimated from bottom pressure and orbital velocity records at a location in 8 m total depth and south of Atchafalaya Bay (from DiMarco and Kelly 1995).

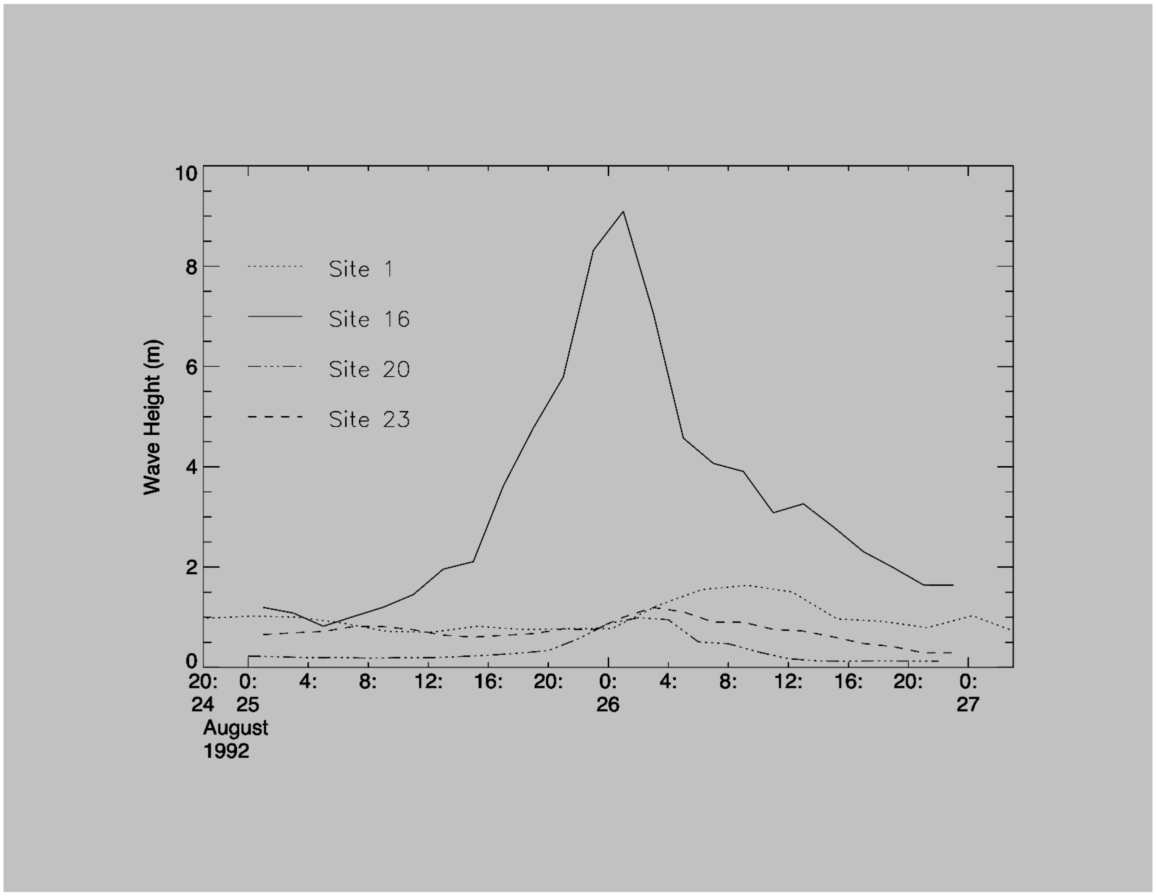

Figure 11. Significant wave height during Hurricane Andrew (August 1992) at four locations across the Texas-Louisiana Shelf. Site 16 (above) was located south of Terrebonne Bay in 18 m total depth and was less than 50 km from the hurricane's eye during closet approach (roughly midnight on 26 August). (from DiMarco et al. 1995)

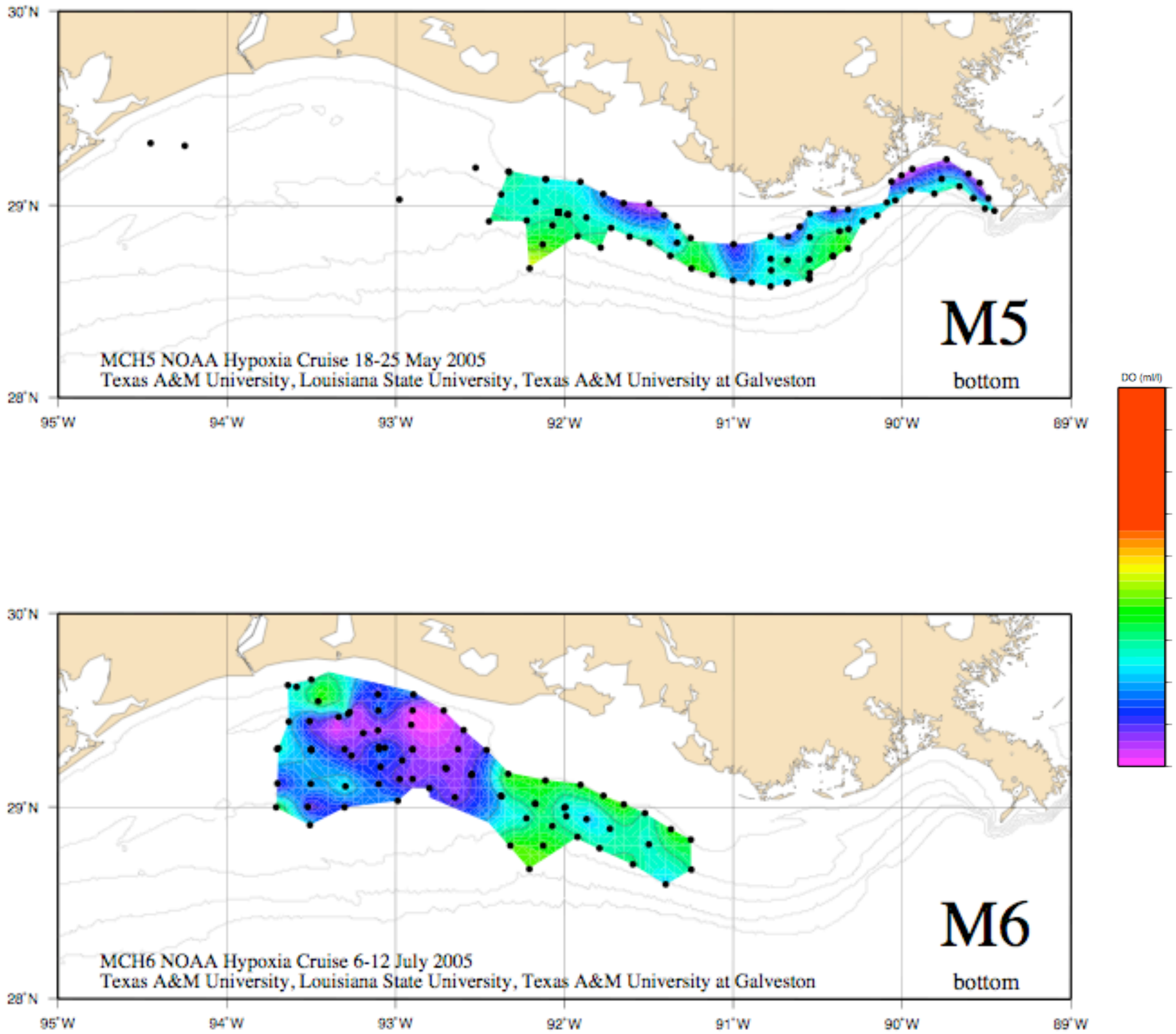

Figure 12. Near-bottom (0.5-1.0 m above bottom) dissolved oxygen concentrations during May (top panel) and July (bottom panel) 2005. Hurricanes Cindy and Dennis impacted the northern Gulf of Mexico 3-9 July. Note: hypoxic conditions were not found between 91°W and 92°W during the July cruise, presumably because of strong mixing conditions during the storms that weakened the pycnocline. Dots are station locations.

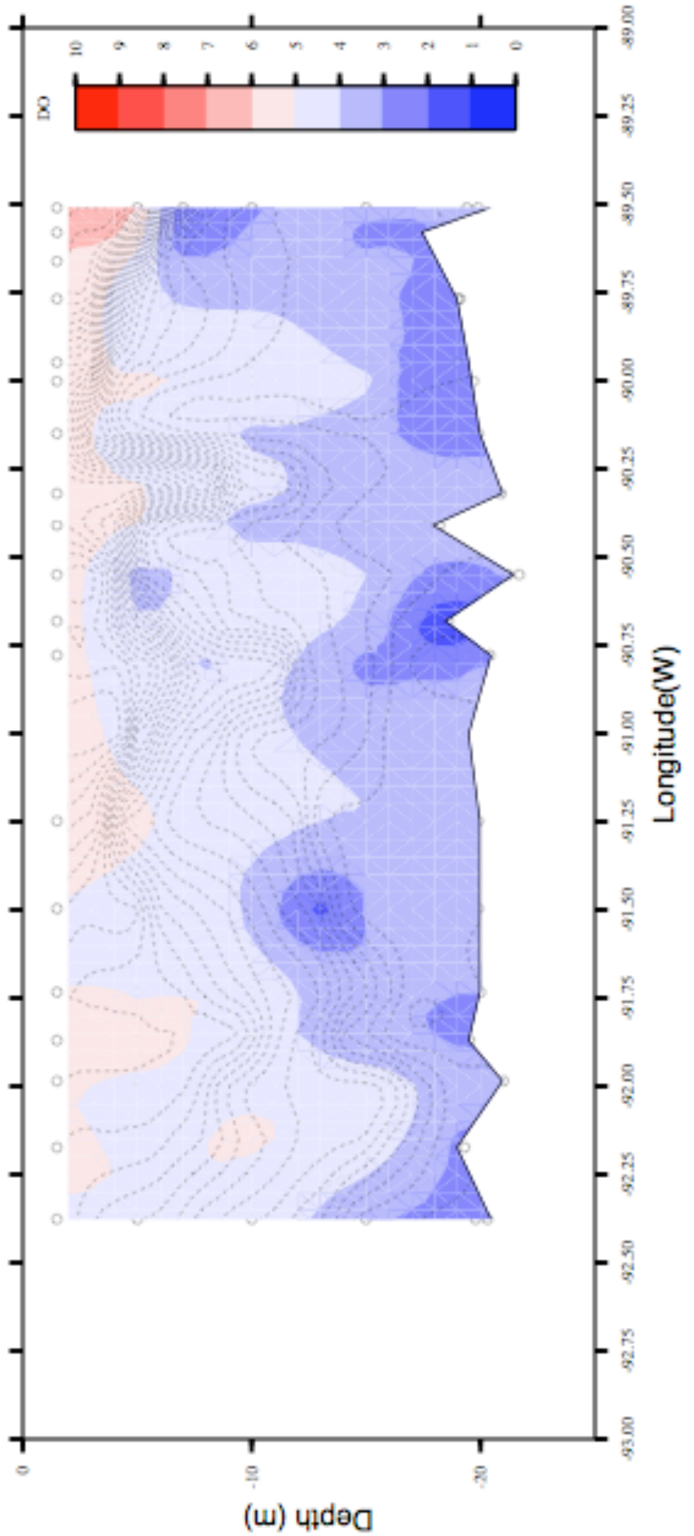

Figure 13. Vertical section of dissolved oxygen concentration (color) and density (dashed lines) along the 20-m isobath between 90.2°W and 93.8°W during May 2005 cruise.

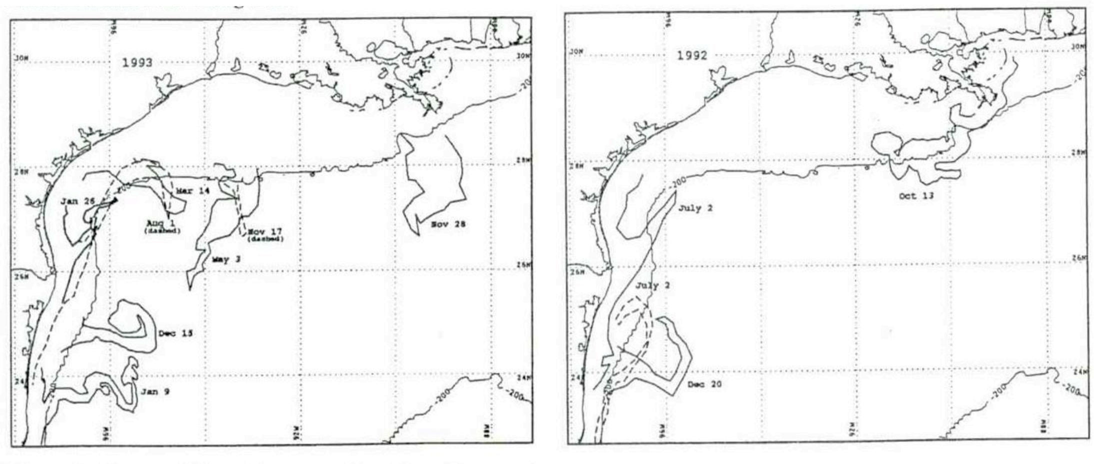

Figure 14. Primary locations of off-shelf movement of shelf water from the Louisiana-Texas shelf as observed in NOAA AVHRR SST data in calendar year (left) 1992 and (right) 1993.

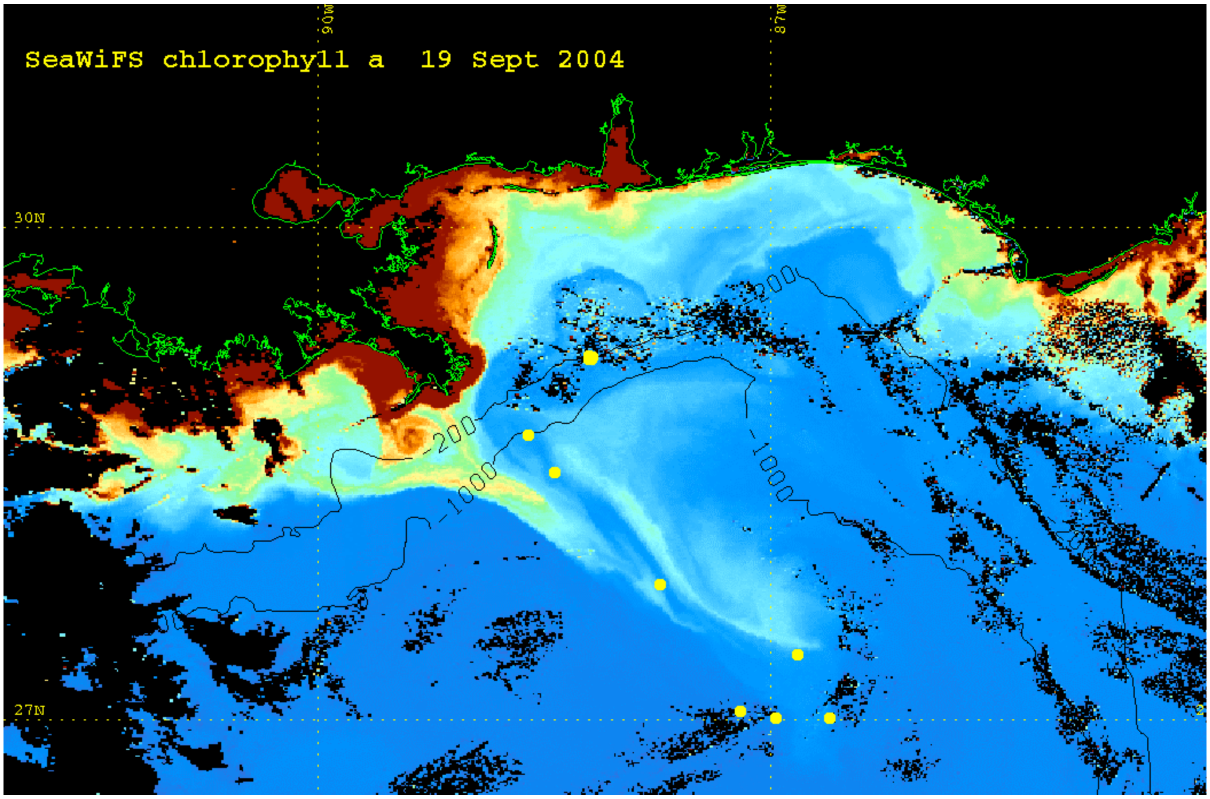

Figure 15. SeaWiFS chlorophyll a image on 19 September 2004 after passage of Hurricane Ivan east of the bird-foot delta showing large-scale flux of pigment rich water into the deep Gulf. The yellow dots indicate tracked positions of NDBC buoy 42040 which broke free of its mooring and moved seaward between slope eddies. Also shown is chlorophyll a enhancement associated with injection of nutrients to the surface within a large cold-core cyclone east of the buoy track (Walker et al., 2005).

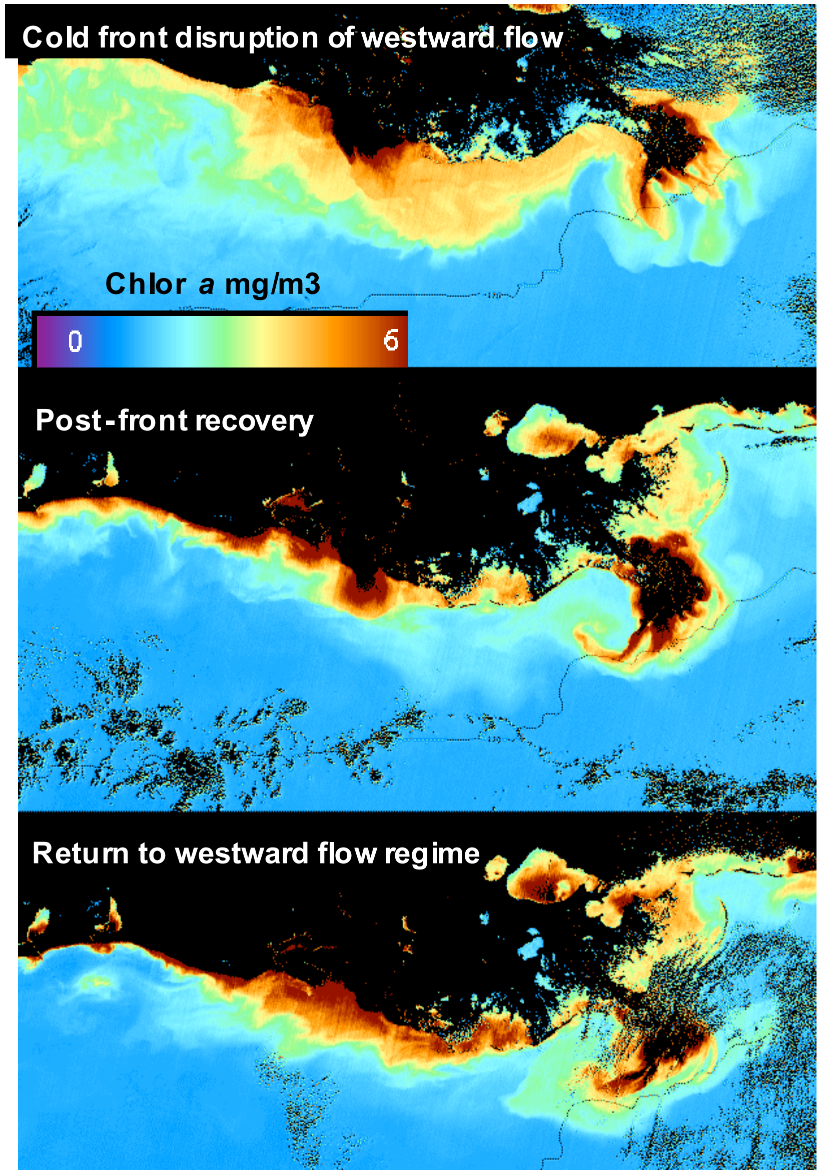

Figure 16. Chlorophyll a imagery obtained by the Oceansat-1 OCM on (top) 1 January 2003; (mid) 29 May 2003 and (bottom) 23 May 2003. Images were chosen to show several modes of wind-driven circulation including disruption of the plumes by eastward and offshore winds (top) and return to westward flow after frontal passage (mid and bottom).

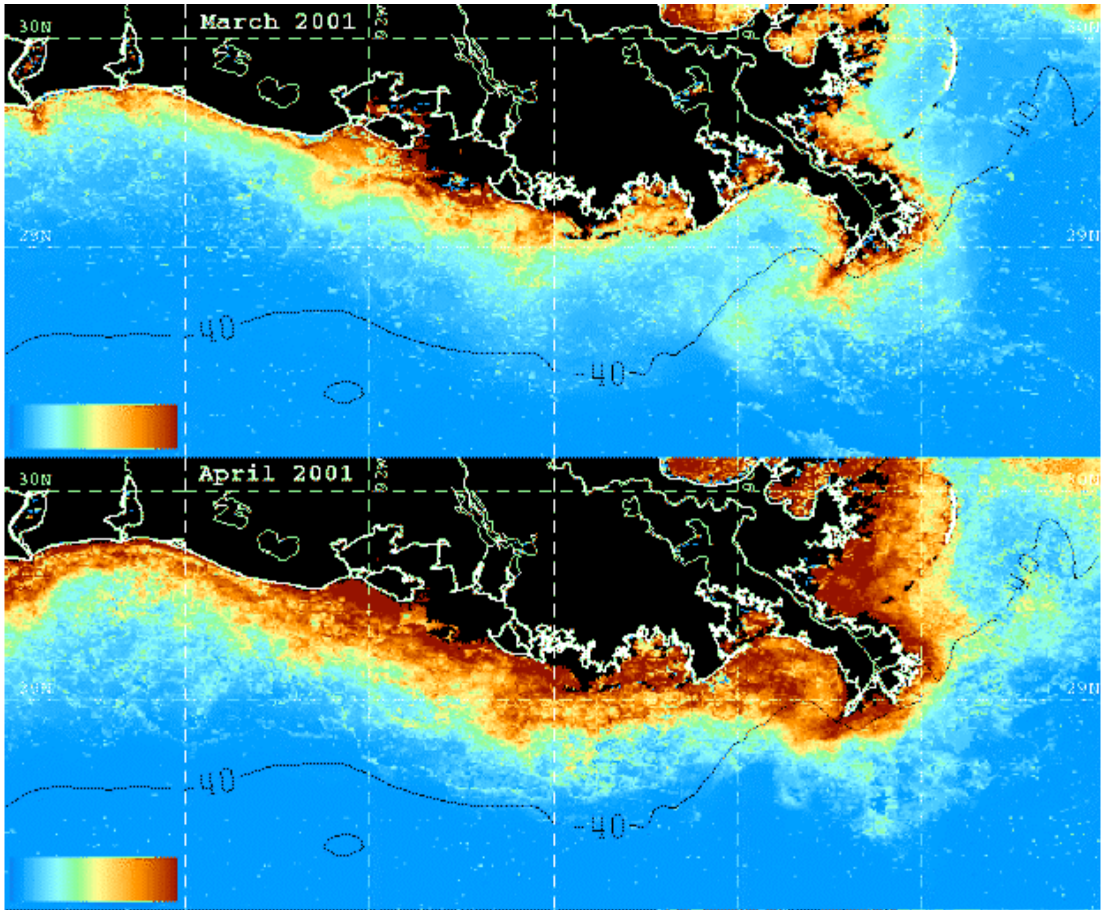

Figure 17. Shelf wide chlorophyll a distribution in March 2001 and April 2001 showing the development of large-scale algal blooms along the coast and in the Louisiana Bight, east of the bird-foot delta, 4-6 weeks after the annual peak in river discharge onto the shelf (From Walker and Rabalais, 2006). The color scale ranges from 0 to 40 mg/m^3.

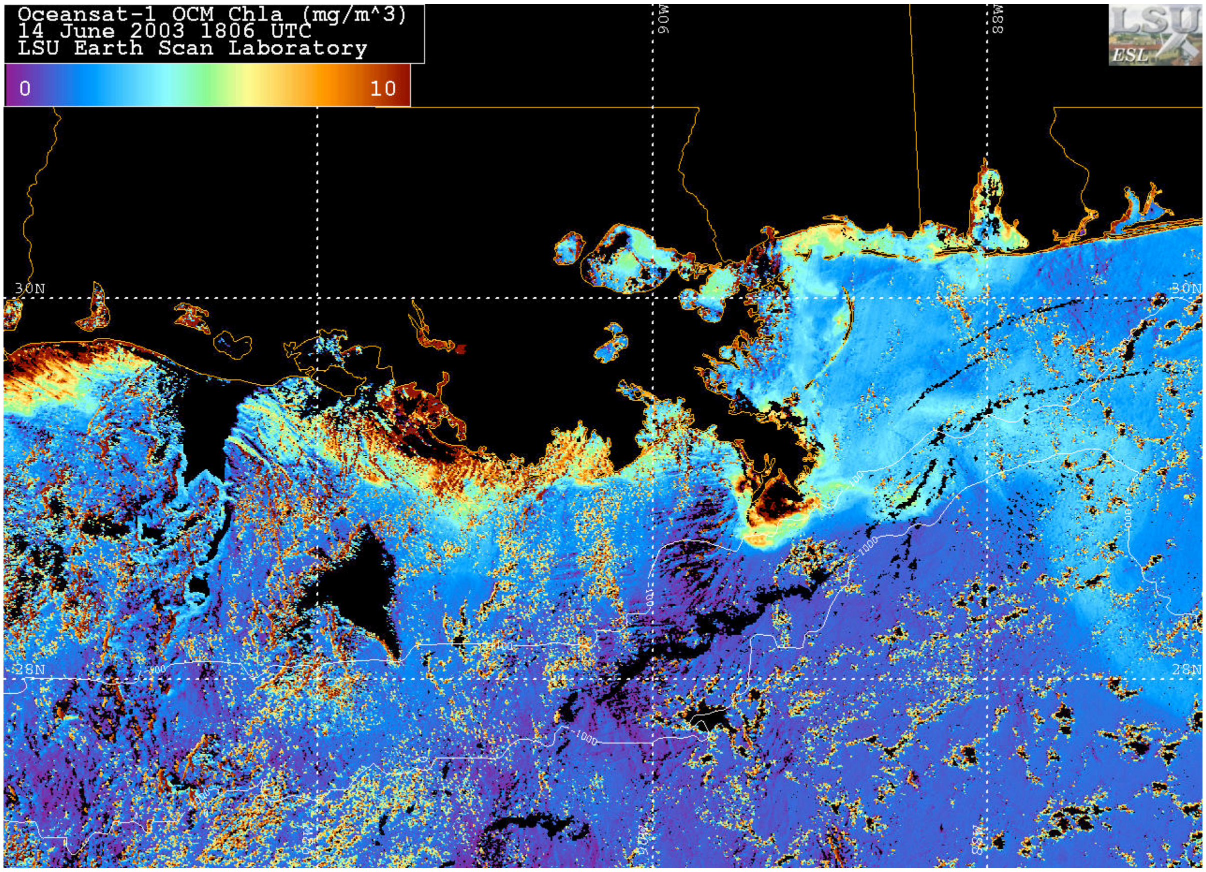

Figure 18. Chlorophyll a image captured by the Oceansat-1 OCM sensor on 14 June 2003 showing the eastward flow of pigment-laden river water driven by both winds and currents along the north flank of a large warm core eddy, south of the delta.

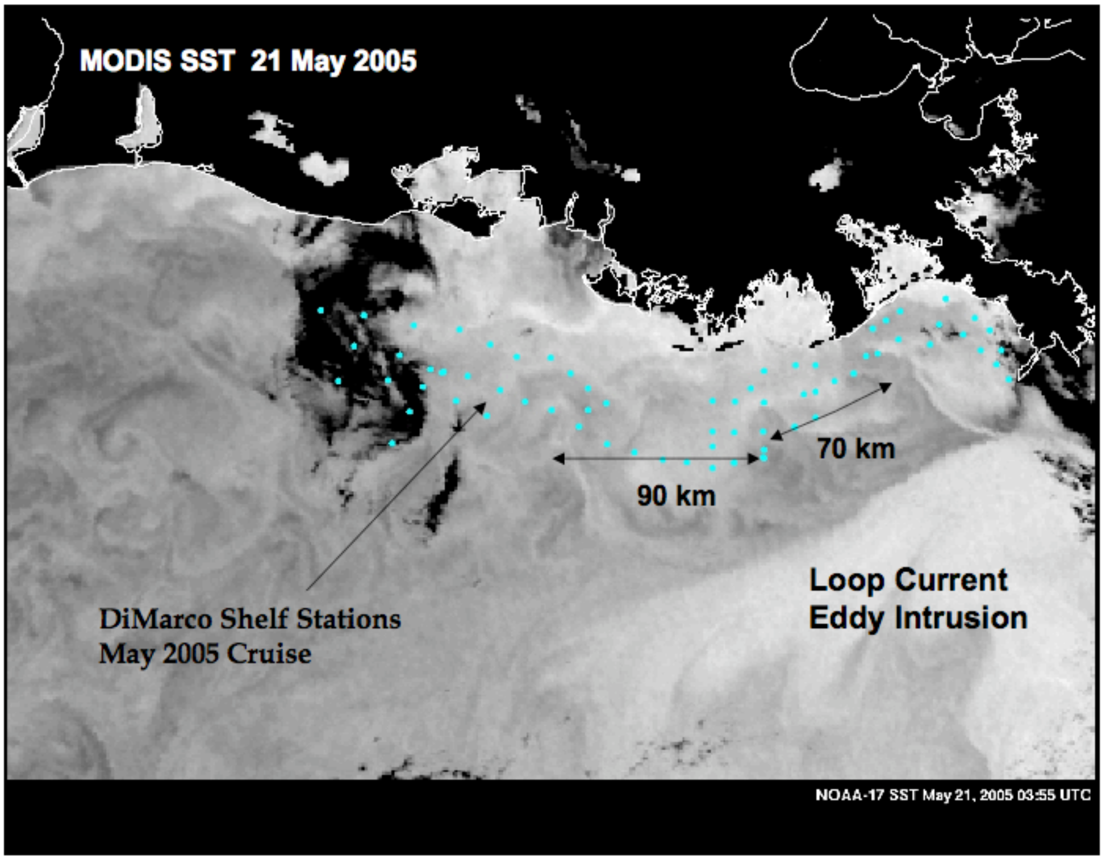

Figure 19. Sea Surface temperature image from the MODIS satellite showing the proximity of a Loop Current anticyclonic eddy to the Louisiana shelf and spatial changes in the surface temperature field which may indicate the presence of shelf waves with wavelengths of 70-90 km. Light blue dots depict station locations occupied on the NOAA-sponsored hypoxia cruise in May 2005.

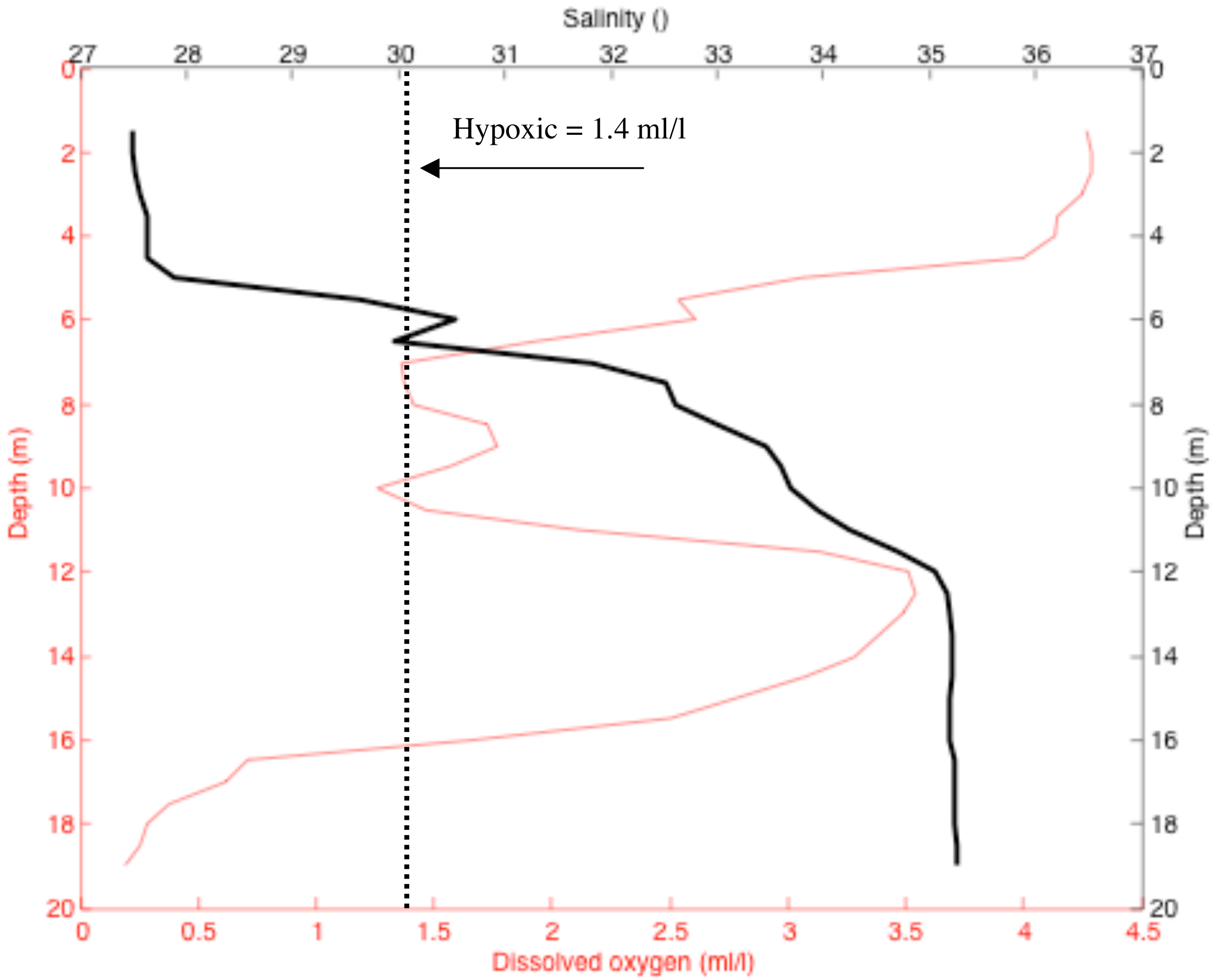

Figure 20. Vertical profile of dissolved oxygen concentration (red) and salinity (black) versus depth from CTD at a location near 29°N, 92°W on 18 August 2005. Total water depth is 20 m. Hypoxia is defined as 1.4 ml/l.